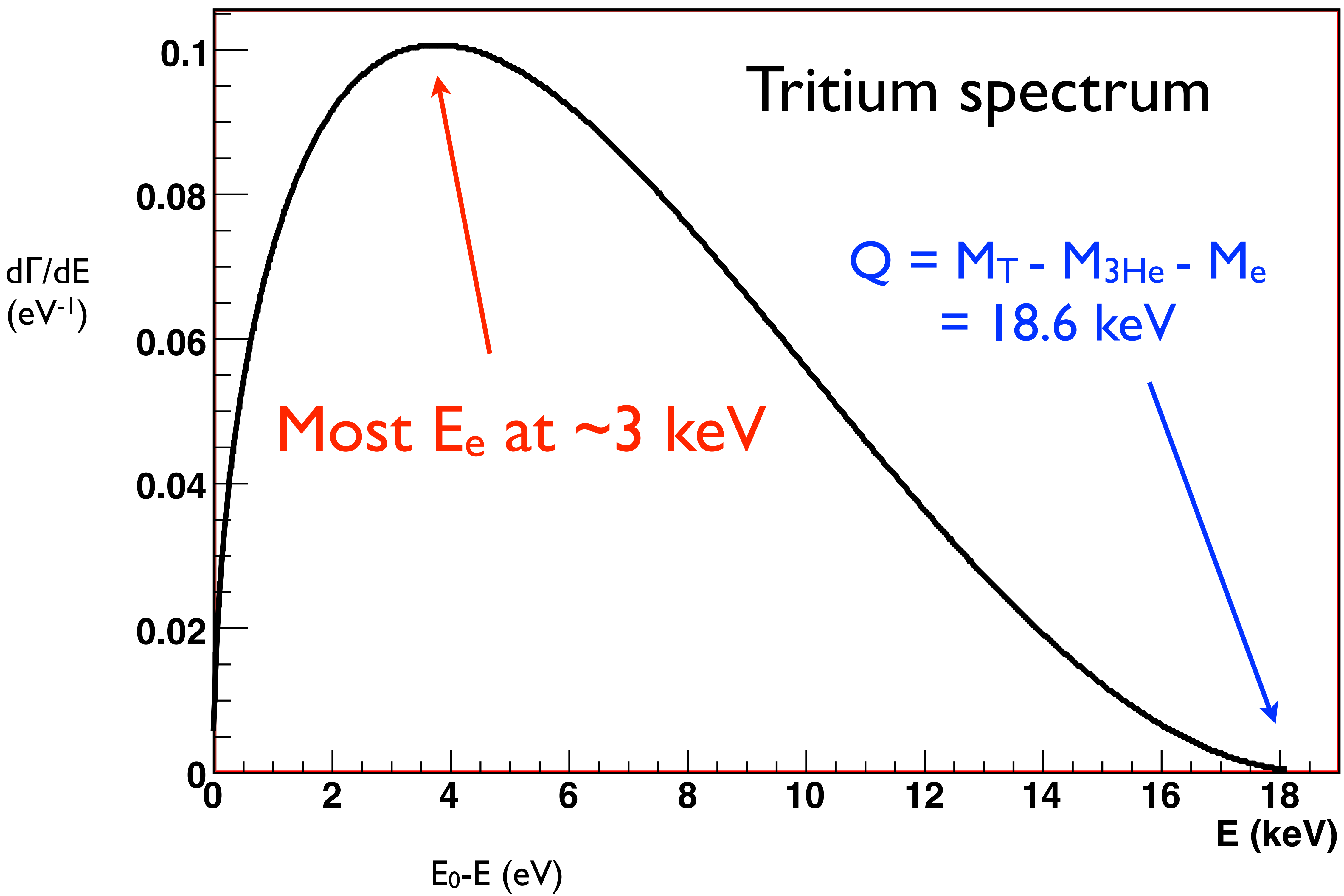
Direct neutrino mass search in tritium: KATRIN and Project 8

Ben Monreal
UC Santa Barbara

Current limit 2.0 eV, BR < 10^{-10}

$$^{3}H \rightarrow {}^{3}He^{+} + e^{-} + \overline{\nu}_e$$

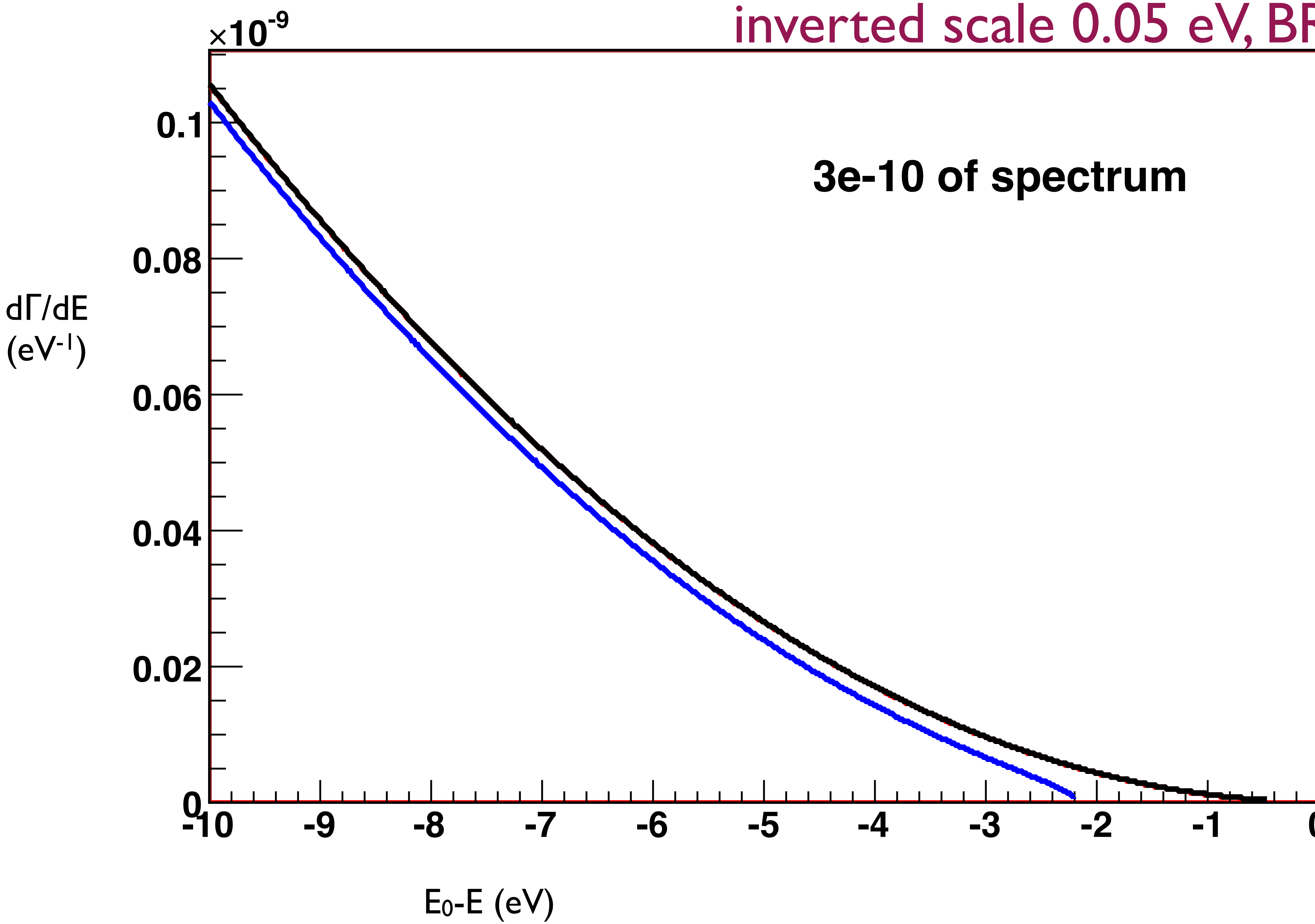


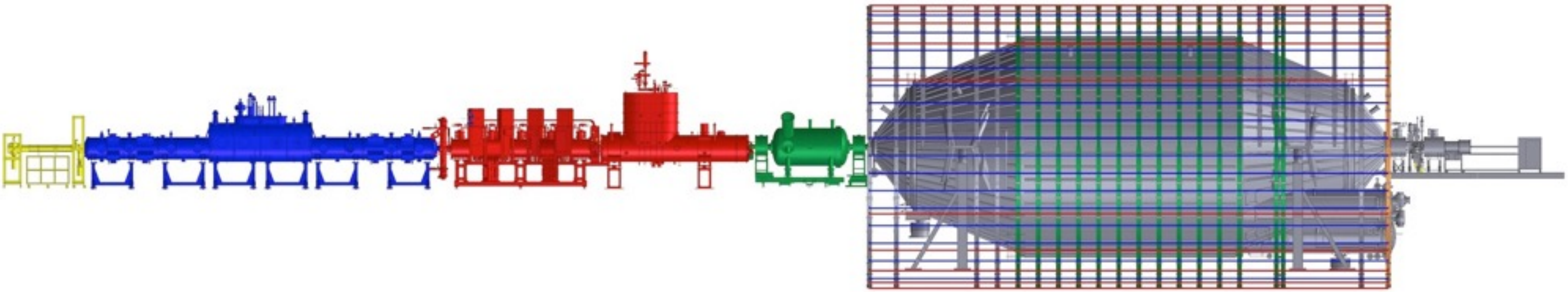
$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$

Current limit 2.0 eV, BR < 10^{-10}

KATRIN goal 0.2 eV, BR < 10^{-12}

inverted scale 0.05 eV, BR < 10^{-14}





KATRIN: 2015—2020 outlook

Ben Monreal, UC Santa Barbara

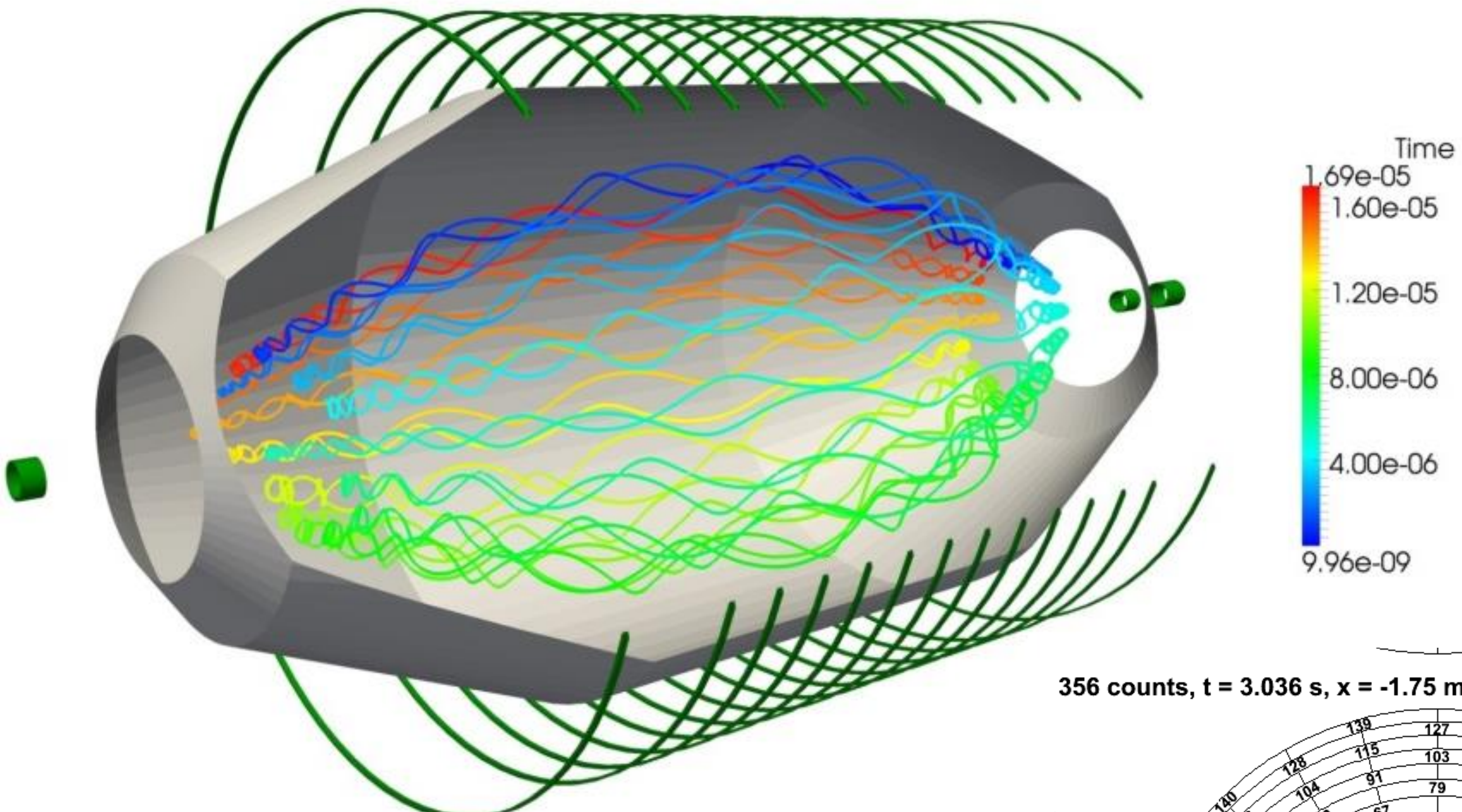
1) Recent spectrometer news: (a) radon, (b) wire repair
2) Source construction news & schedule
3) Stat & systematic error outlook
4) Upgrade ideas and needs

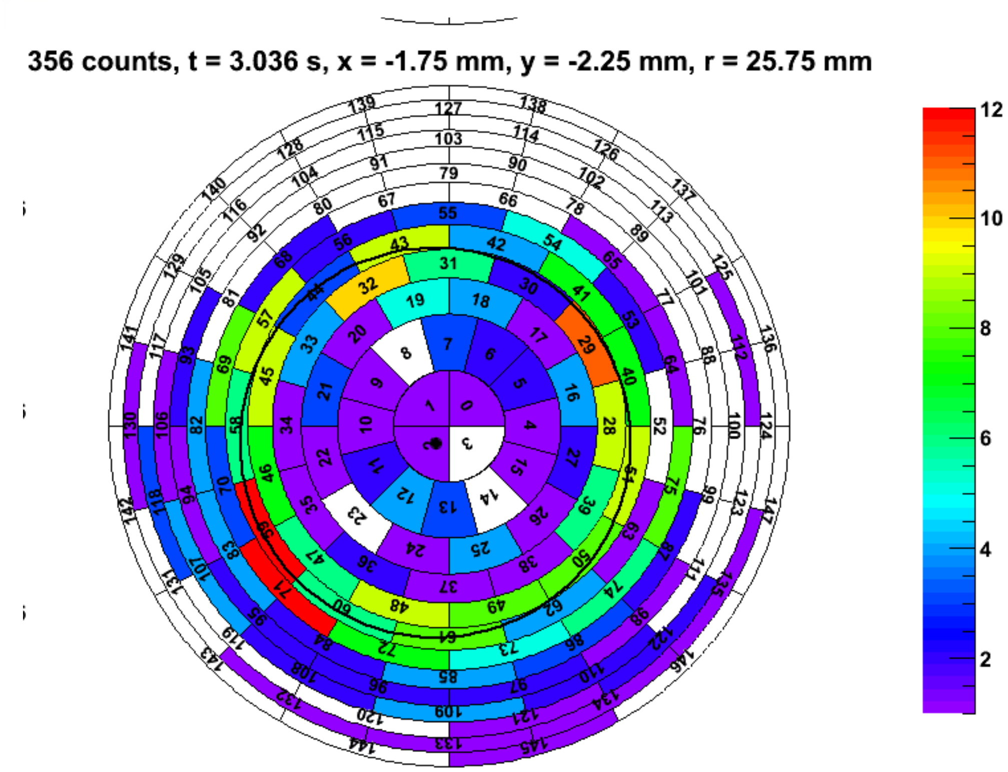
1: Spectrometer news (a) Radon

Radon decay in spectrometer = ionizes residual gas at high potential = background e⁻

Electrons:

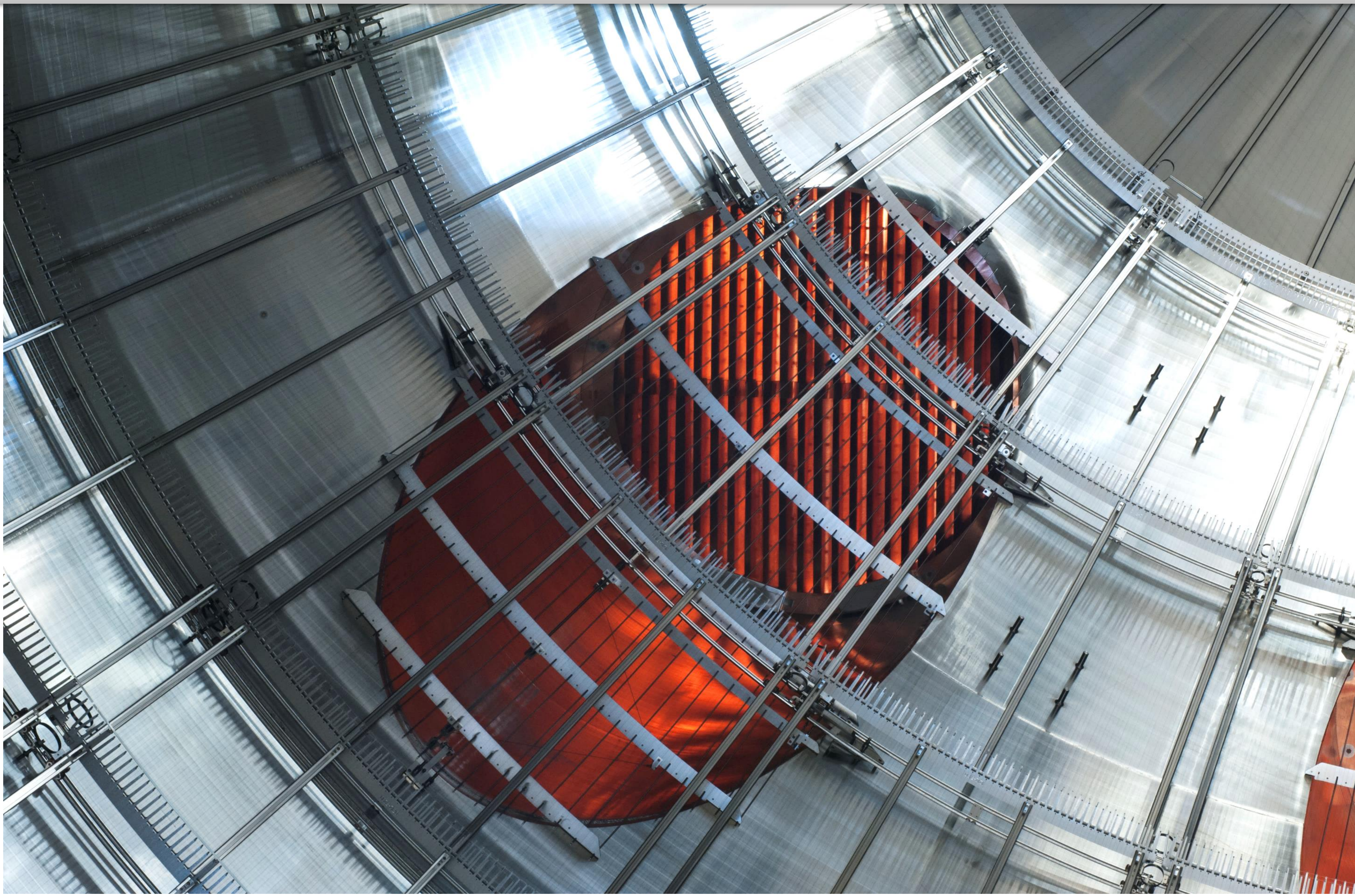
Energy (keV)	Intensity
Auger L	8.33
CE K	37.50
Auger K	59.7
CE L	113.66
CE M	126.45
CE K	178.125
CE K	200.45
CE L	254.291
CE M	267.081
CE L	276.62
CE M	289.41
CE K	308.705
CE L	384.871
CE M	397.661
CE K	424.49
CE L	500.66





1: Spectrometer news (a) Radon

Newly-installed cryopumping capacity = LN2-cooled baffles in front of NEG pumps



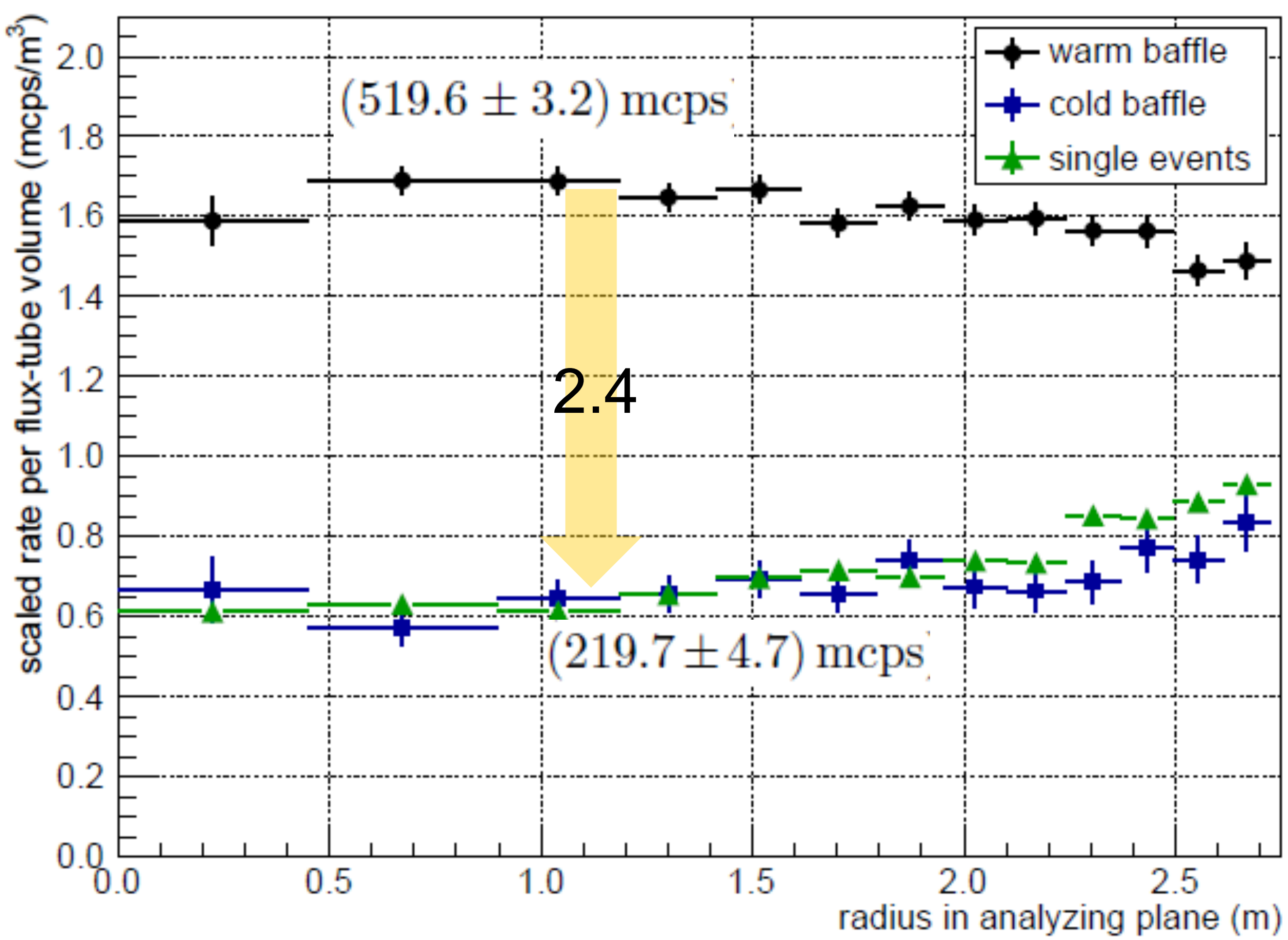
Drexlin

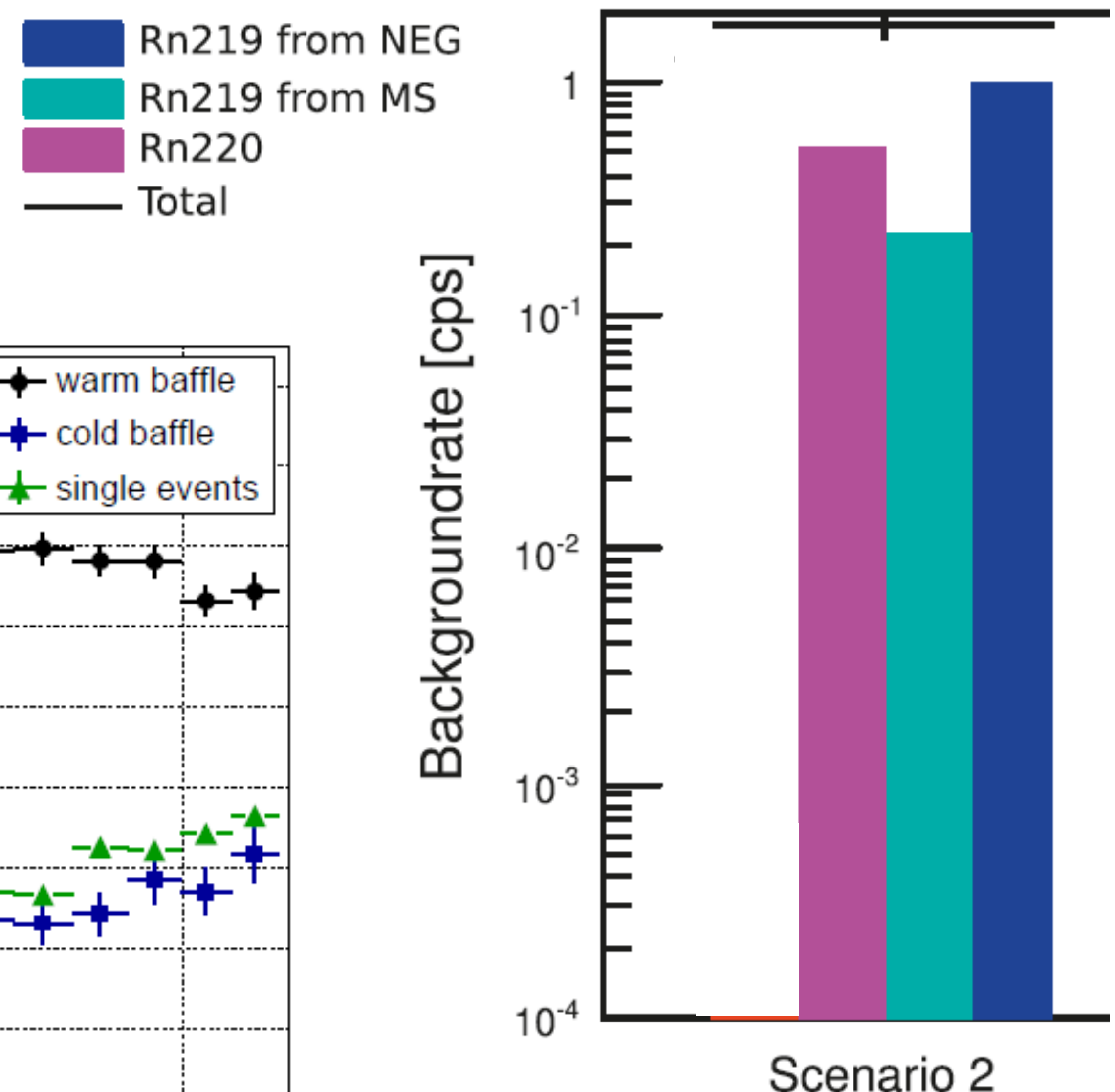
Baffles are good at pump-port Rn removal, less good at spectrometer volume

observed single background at SDS-1

- expected Rn background: O (1 cps)

9 G setting



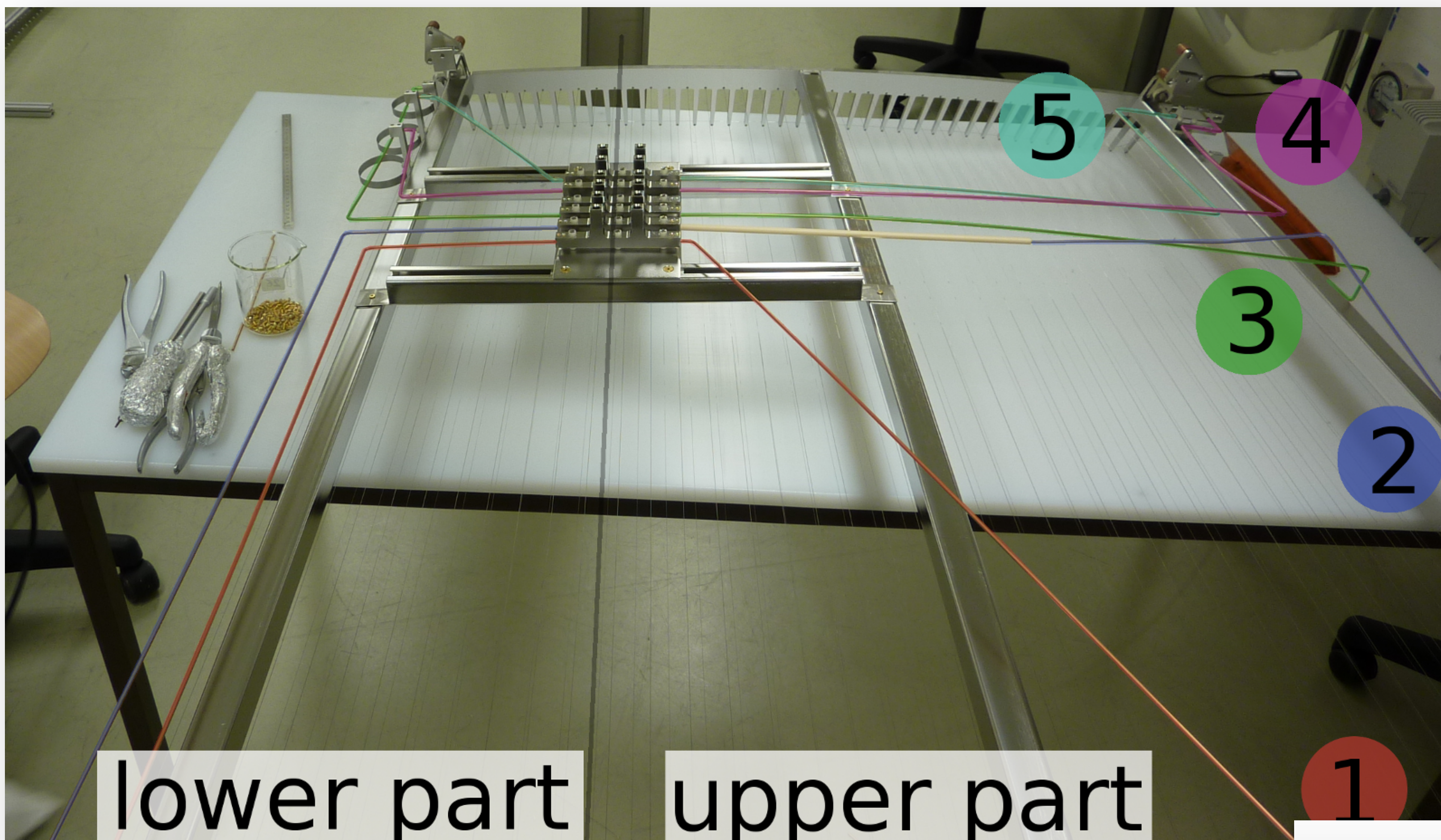


G. Drexlin – radon suppression

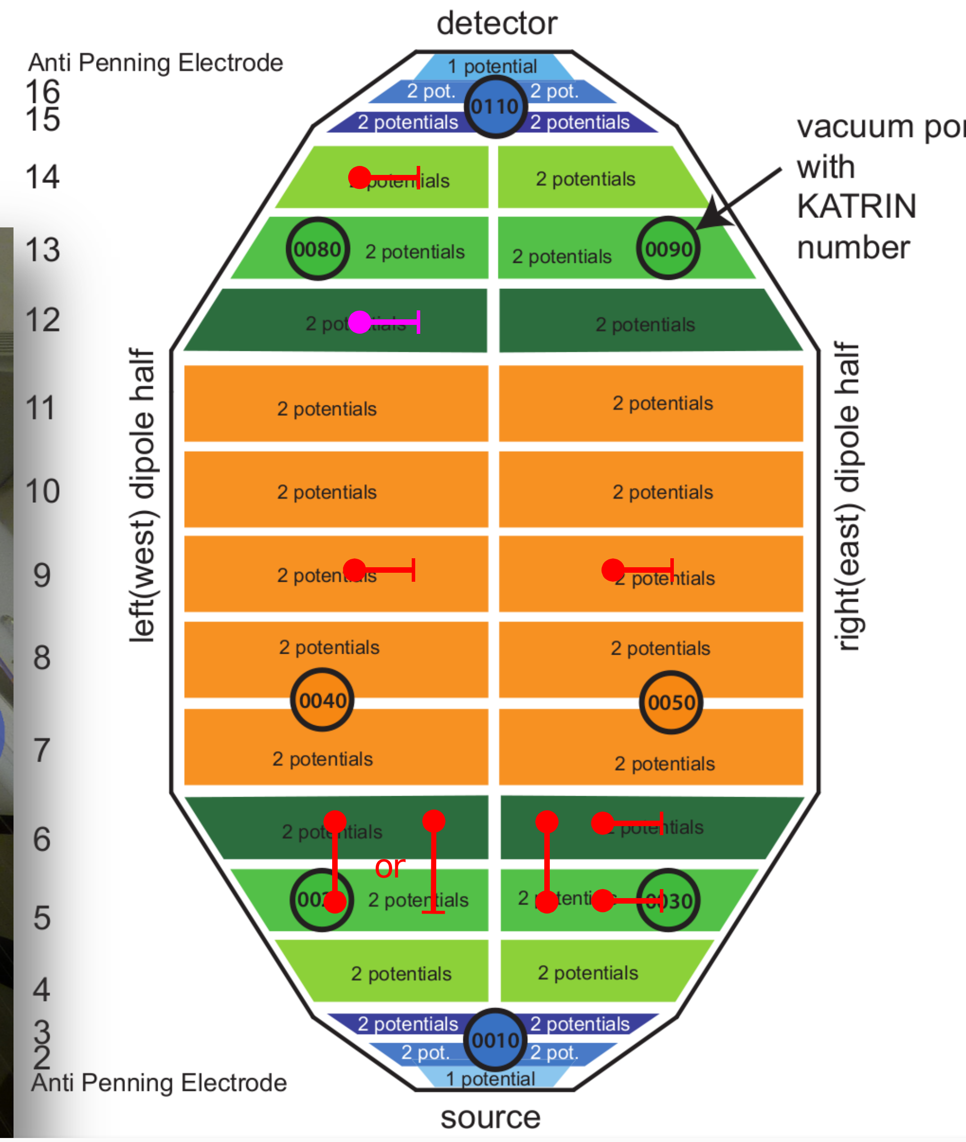
Drexlin

Inner Electrode Repair

- **Situation of the Inner Electrode:**
  - CuBe rods used to distribute wire electrode potentials behind the wire layers deformed during baking above 200 °C.
  - Several short circuits prevent us from using double layer configuration.



status of 20.01.13

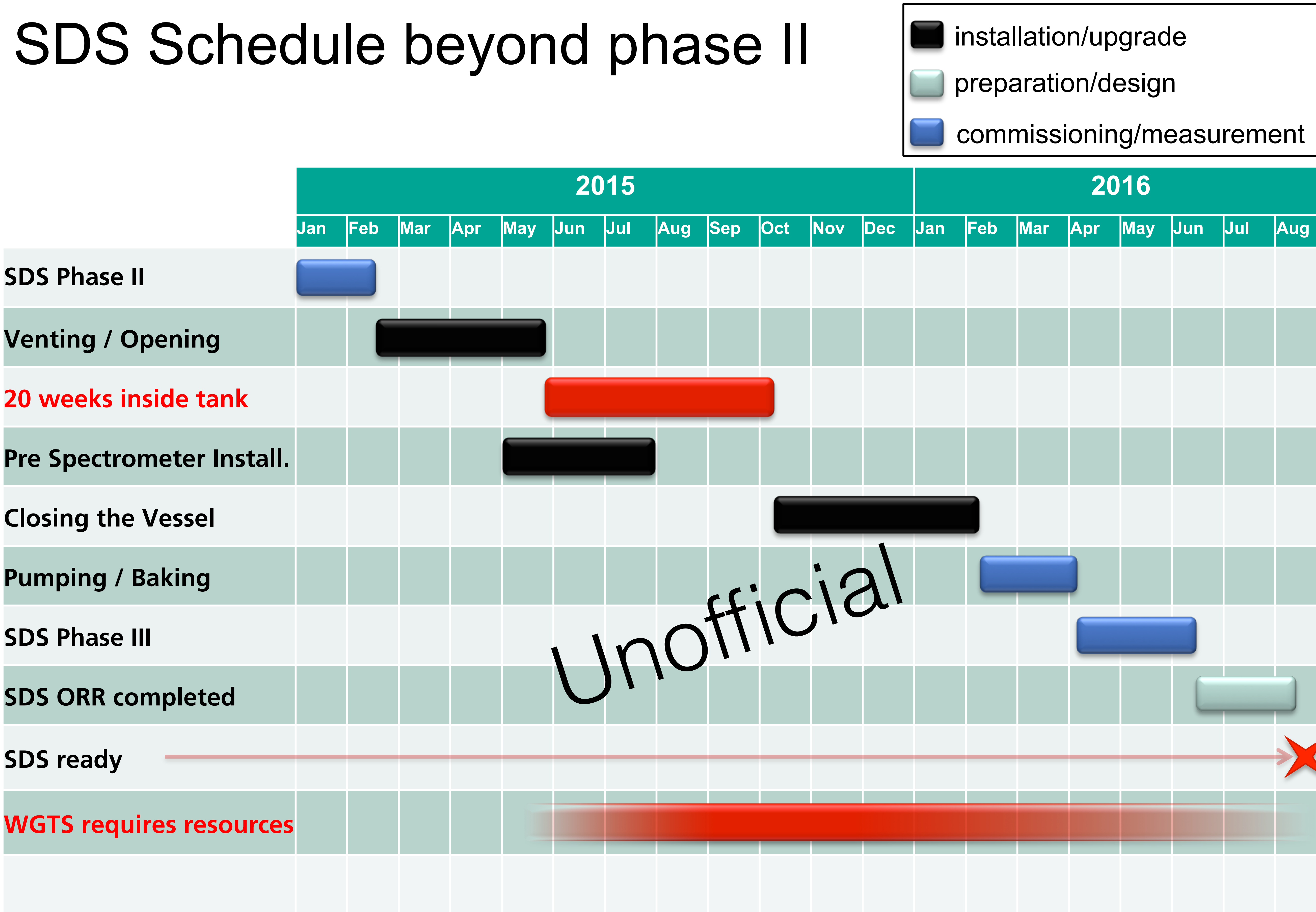


Without double-layer wire configuration, low-energy wall electrons can wander into flux tube

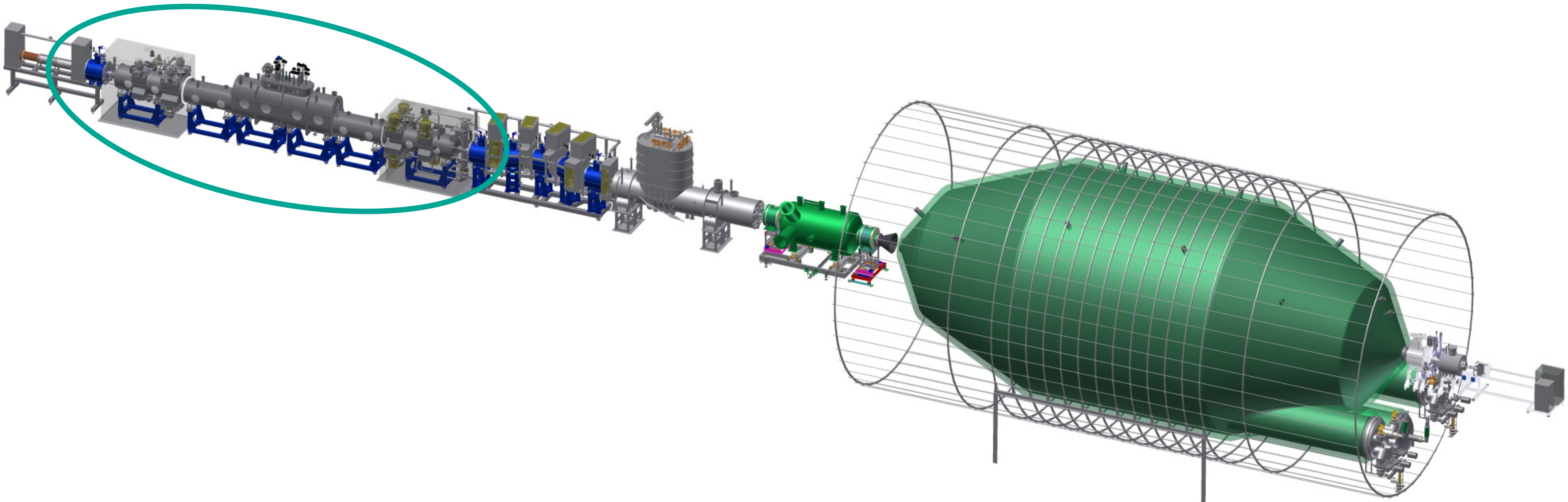
within a single ring.

Thummler

SDS Schedule beyond phase II



The Windowless Gaseous Tritium Source



- T_2-injection 1.8 mbar l/s = 1.7*10^{11} Bq/s = 40 g tritium per day
- Temperature stabilized (ΔT<30 mK) beamline
- 7 superconducting solenoids in driven mode
- Challenging system regarding cryogenics, vacuum, magnet system
- Currently under construction

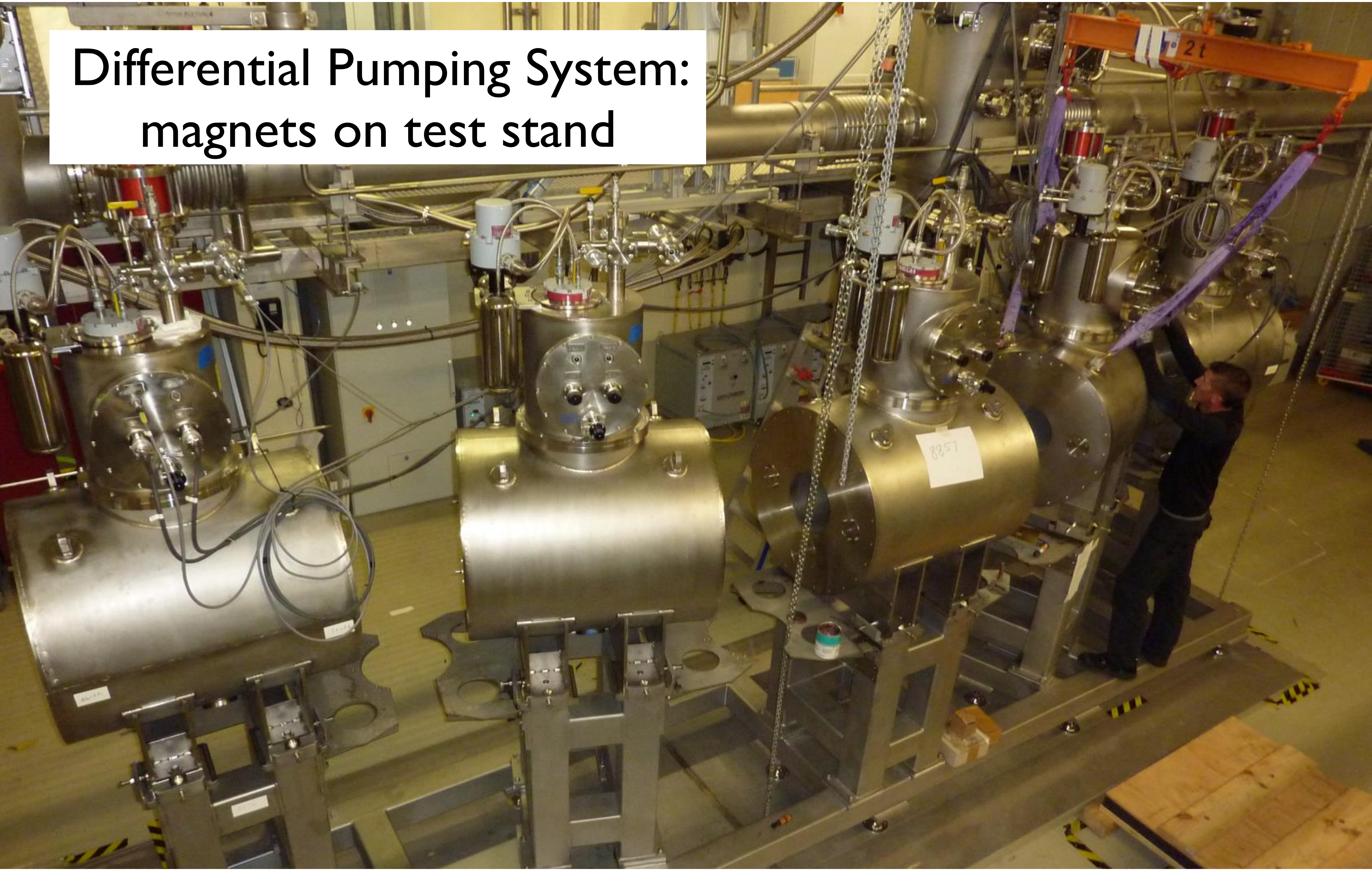
WGTS Mounting

Final WGTS Mounting continues

- Huge assembly tooling was prepared in time
- 6/15 final mounting steps have been concluded without any mayor incidents
- Skilled an experienced personal in charge of mounting strategy and control

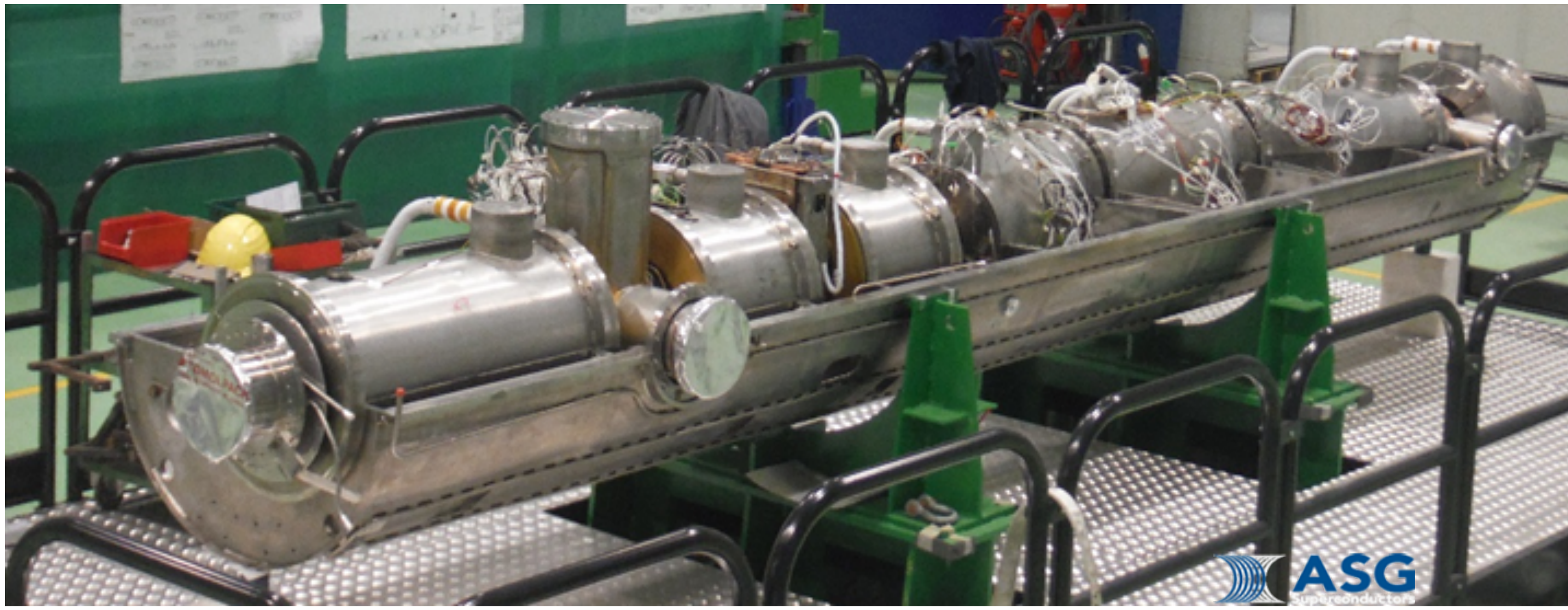
Fränkle & Kosmider

Differential Pumping System: magnets on test stand



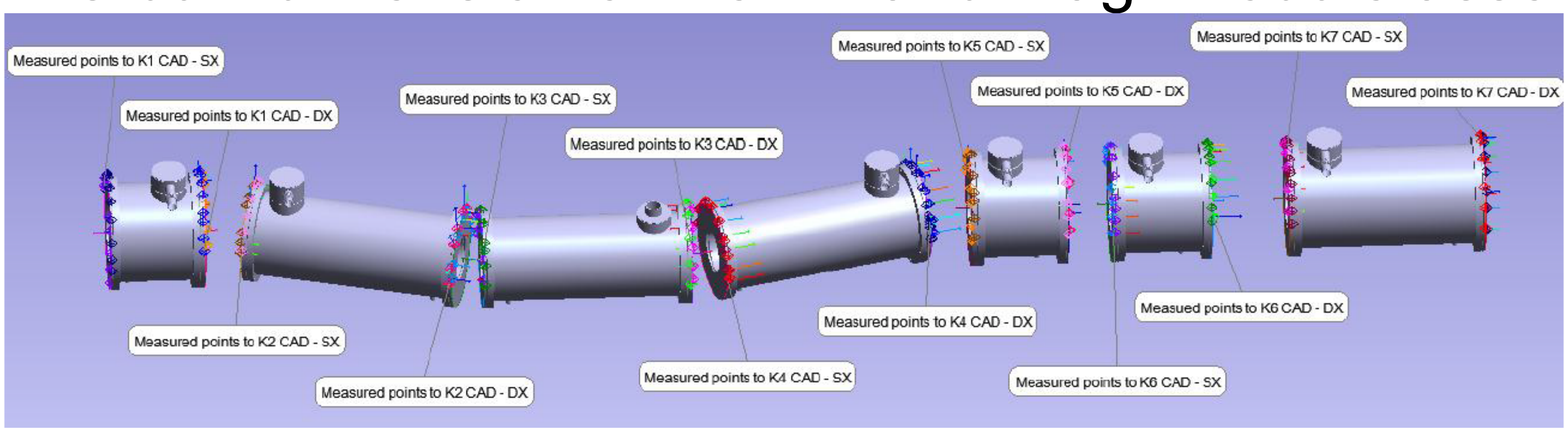
Cryogenic Pumping System

- Cold mass with beam tubes+ports, 7 magnet modules, supports, piping



Feb. ’14

- As-built dimension of the BT and Mag.-Module assembly



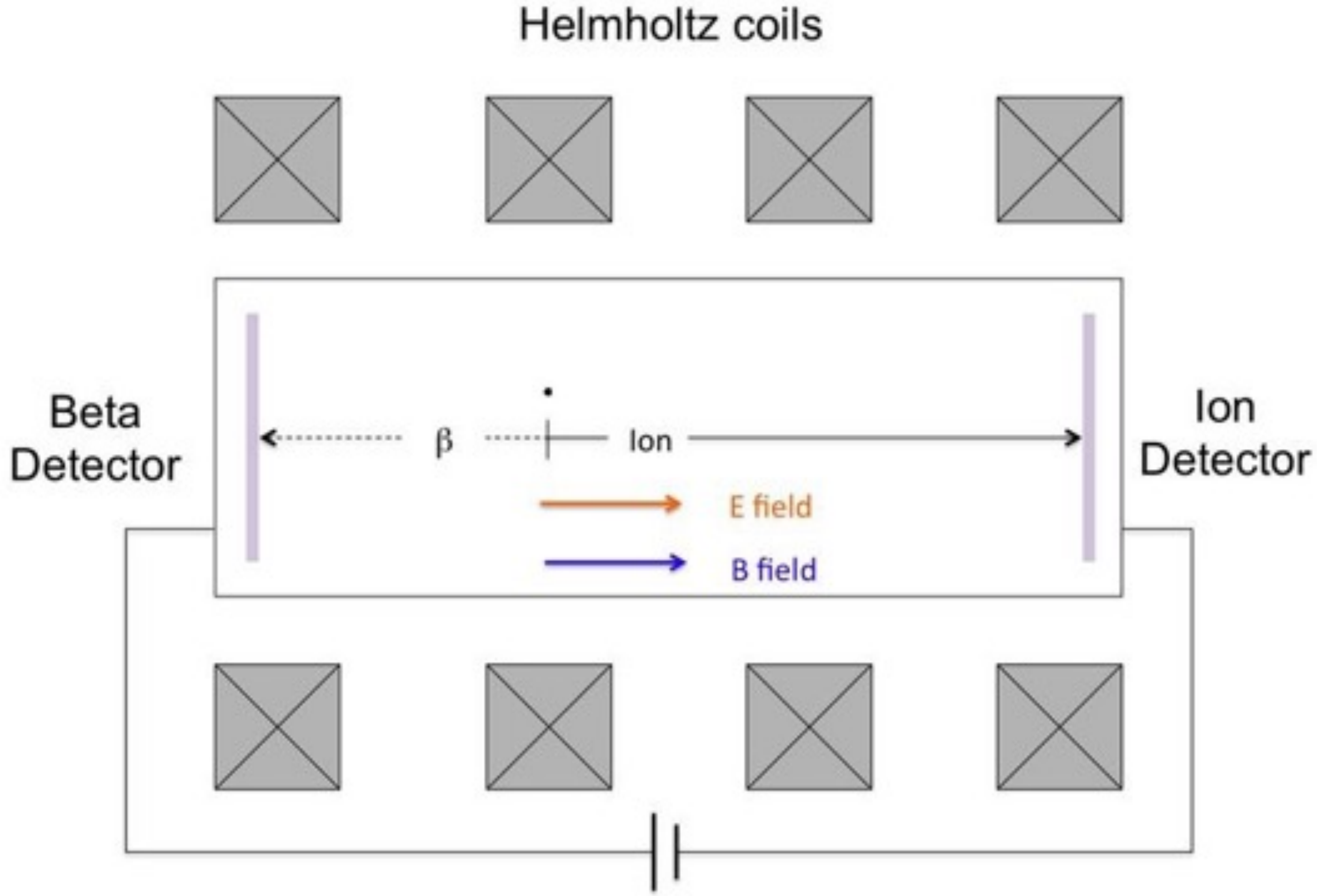
***apis**ensor.com*

Measurement by laser tracker at room temperature
→Dimensions at cold condition is needed for magnetic field calculation!

Systematics progress

source of systematic shift	achievable/projected accuracy	systematic shift $\sigma_{\text{syst}}(m_\nu^2)[10^{-3}\text{eV}^2]$
description of final states	$f < 1.01$	< 6
T^- ion concentration $n(T^-)/n(T_2)$	$< 2 \cdot 10^{-8}$	< 0.1
unfolding of the energy loss function (determination of f_{res})		< 2 < 6 (including a more realistic e-gun model)
monitoring of $\rho\, d$ $[E_0 - 40\,\text{eV}, E_0 + 5\,\text{eV}]$	$\Delta\epsilon_T/\epsilon_T < 2 \cdot 10^{-3}$ $\Delta T/T < 2 \cdot 10^{-3}$ $\Delta\Gamma/\Gamma < 2 \cdot 10^{-3}$ $\Delta p_{\text{inj}}/p_{\text{inj}} < 2 \cdot 10^{-3}$ $\Delta p_{\text{ex}}/p_{\text{ex}} < 0.06$	$< \frac{\sqrt{5} \cdot 6.5}{10}$
background slope	$< 0.5\,\text{mHz/keV}$ (Troitsk)	< 1.2
HV variations	$\Delta\text{HV}/\text{HV} < 3\,\text{ppm}$	< 5
potential variations in the WGTS	$\Delta U < 10\,\text{meV}$	< 0.2
magnetic field variations in WGTS	$\Delta B_S/B_S < 2 \cdot 10^{-3}$	< 2
elastic $\text{e}^- - \text{T}_2$ scattering		< 5
identified syst. uncertainties	$\sigma_{\text{syst,tot}} = \sqrt{\sum \sigma_{\text{syst}}^2} \approx 0.01\,\text{eV}^2$	

conservative 2004 design report $\sigma_{\text{sys,tot}} = 0.017\ \text{eV}^2$

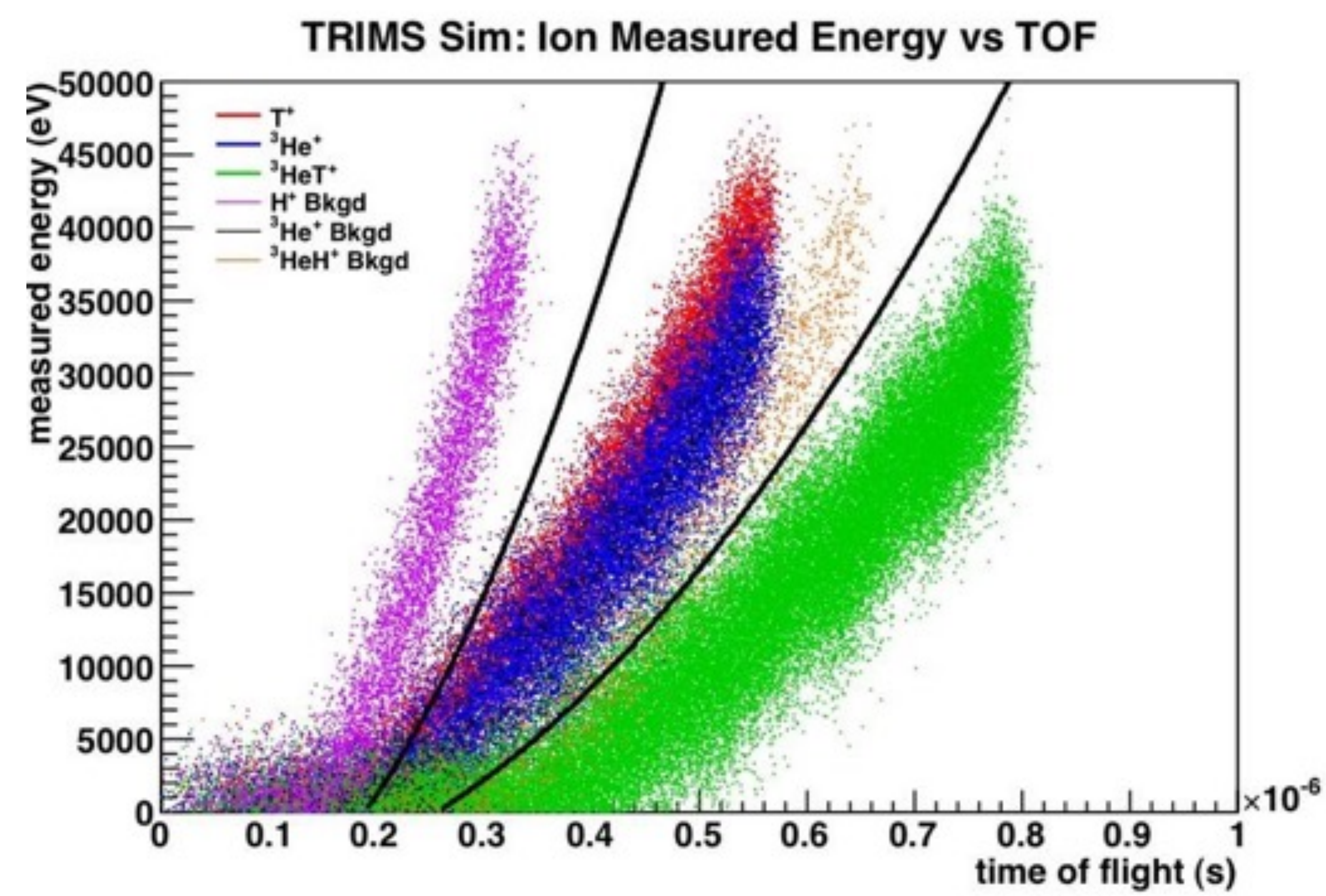


TRIMS

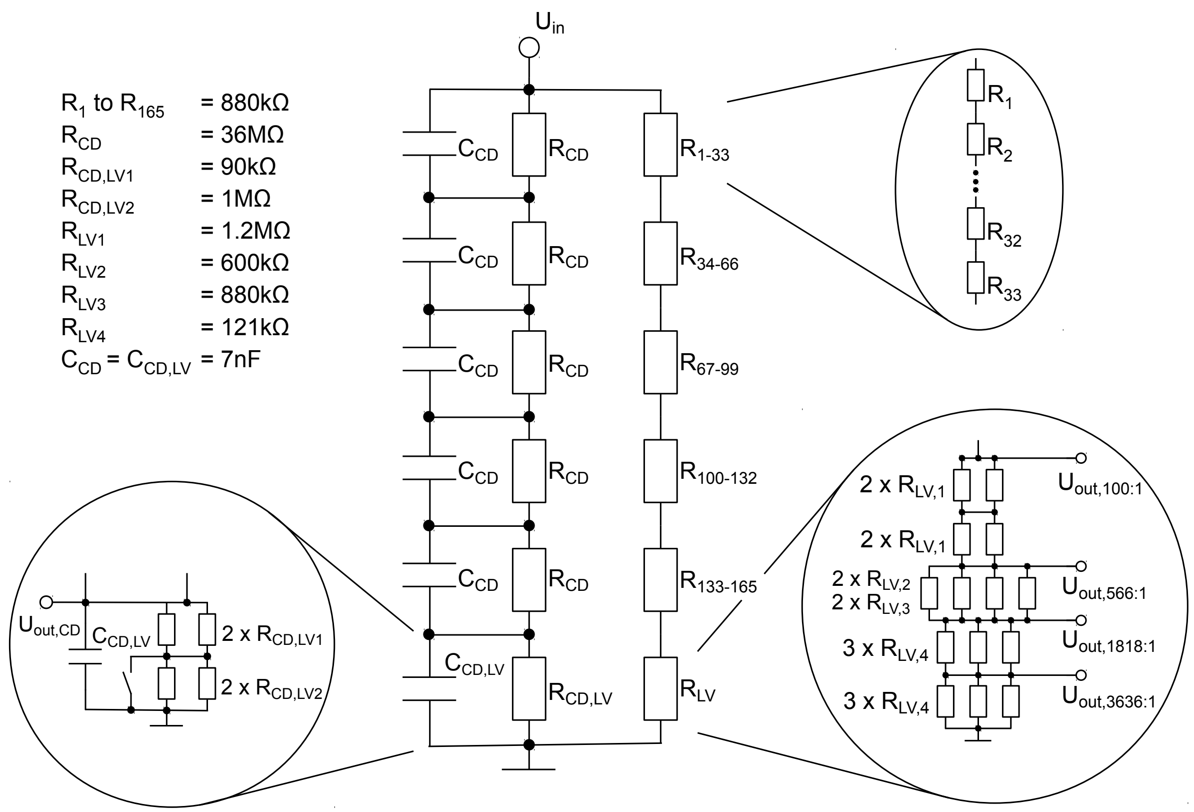
L. Bodine, D. Parno, H. Robertson
CENPA/UW

Goal: check accuracy of molecular theory for
$T_2 \rightarrow (^3HeT)^{+*}$ e- $\bar{\nu}$
Systematic treatment at KATRIN:
$\sigma_E((^3HeT)^{+*}) = 0.3 \pm 0.003$ eV

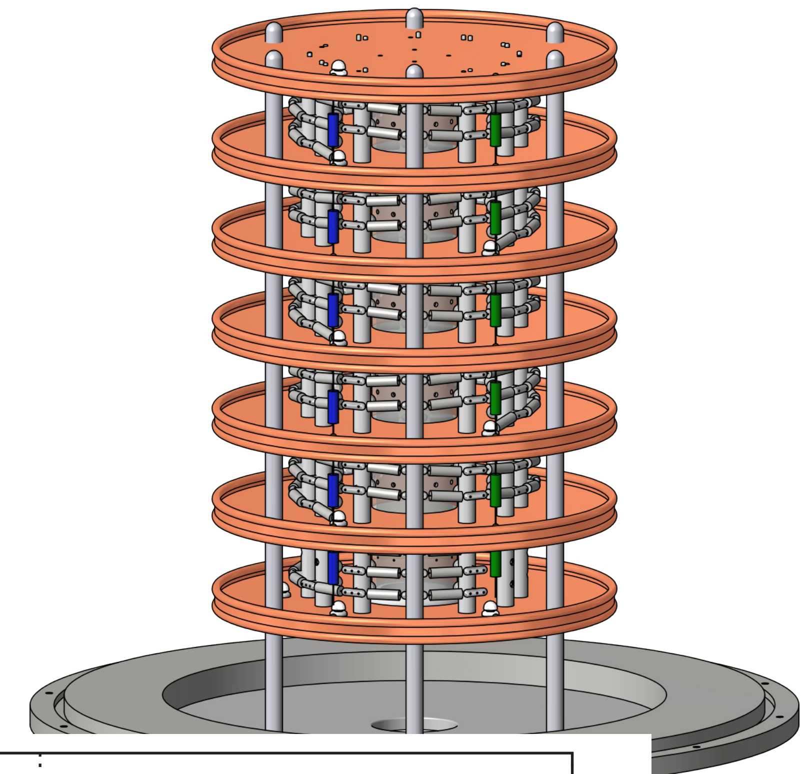
Method: measure ratios of dissociation decays
$T_2 \rightarrow {}^3He^+$ T e- $\bar{\nu}$
$T_2 \rightarrow {}^3He$ T^+ e- $\bar{\nu}$
$T_2 \rightarrow (^3HeT)^+$ e- $\bar{\nu}$
predicted by same calc.

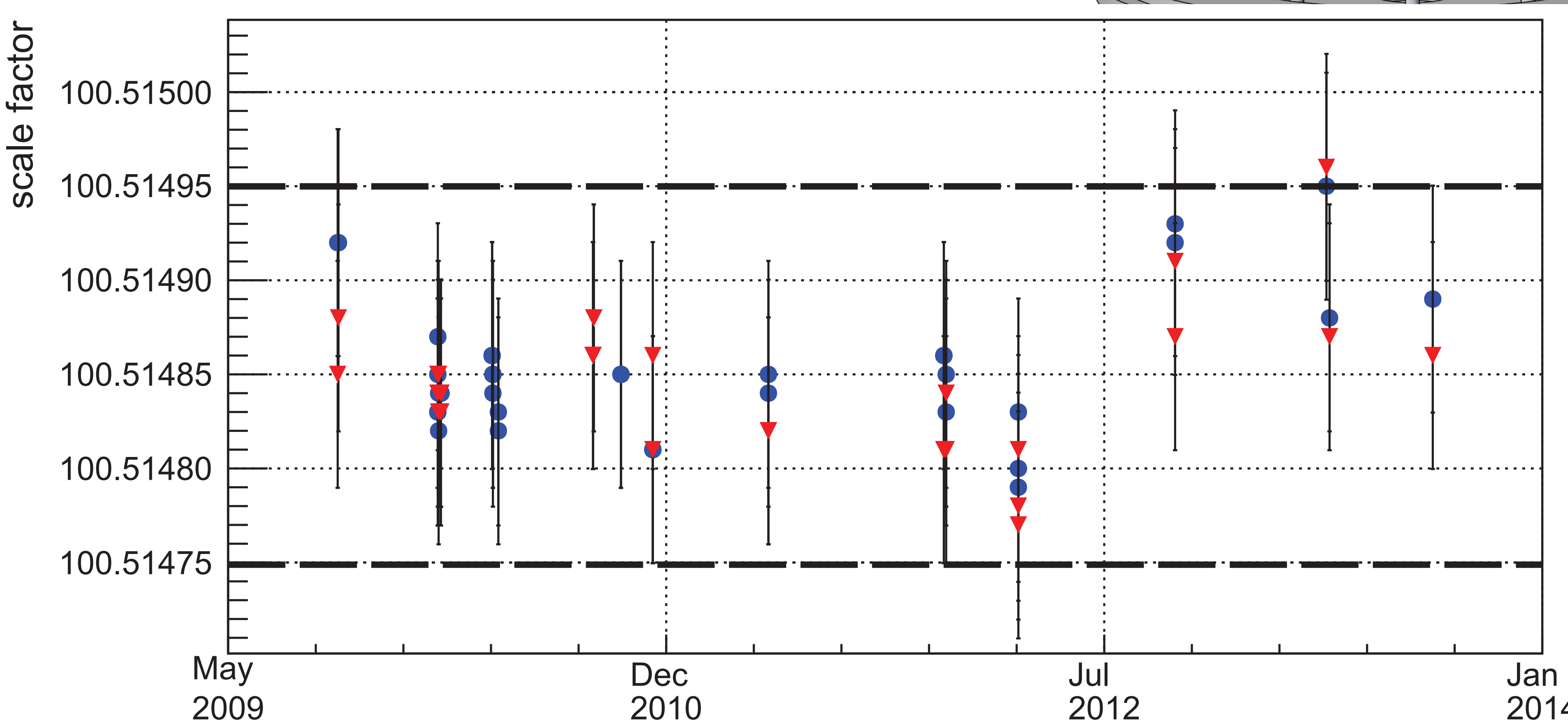


High-voltage stability



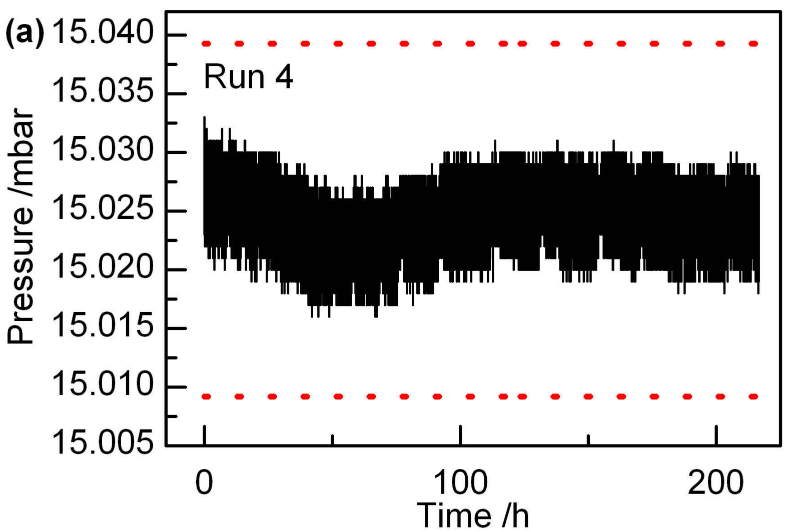
Design requirement: ΔV/V < 1.5 ppm/month
Obtained: 0.1 ppm/month





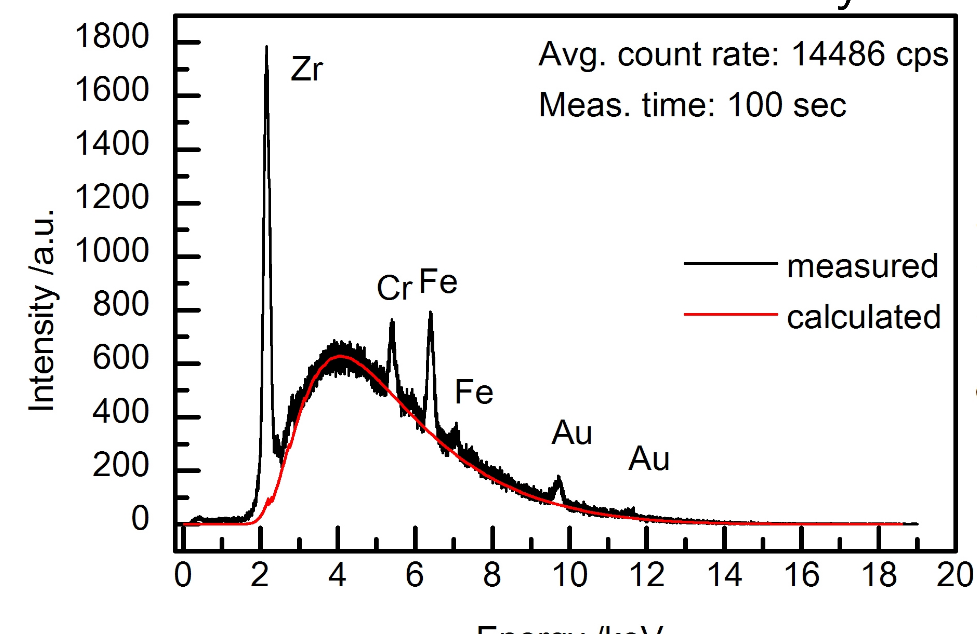
Stephan Bauer
Ph.D. thesis,
Münster 2013

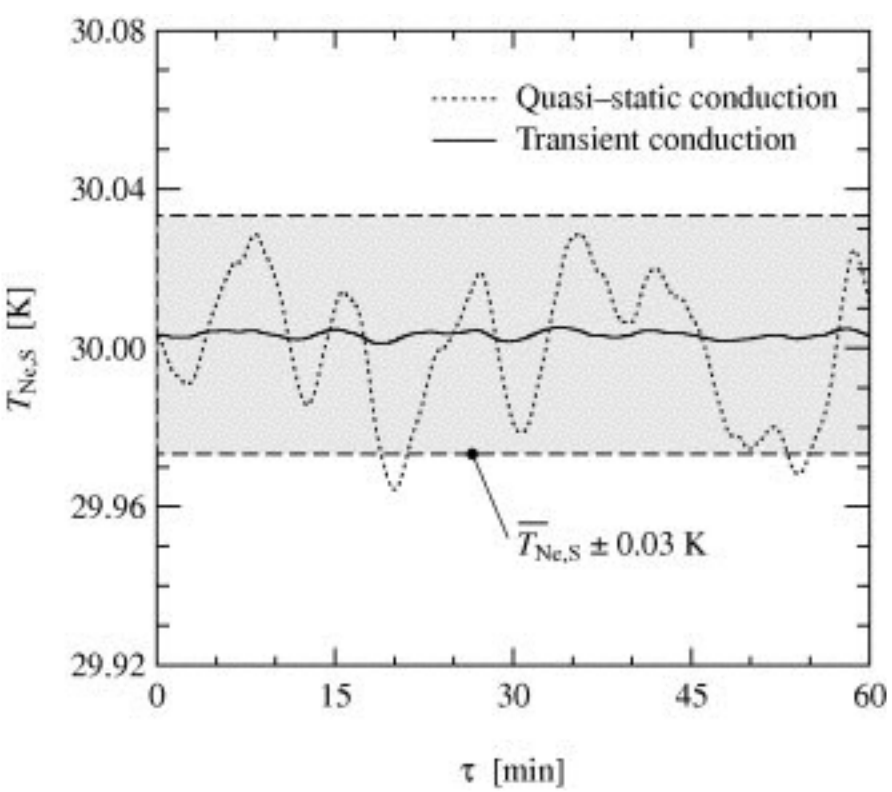
T_2 source stability



Injection pressure stability
require 0.1%
obtained 0.01%

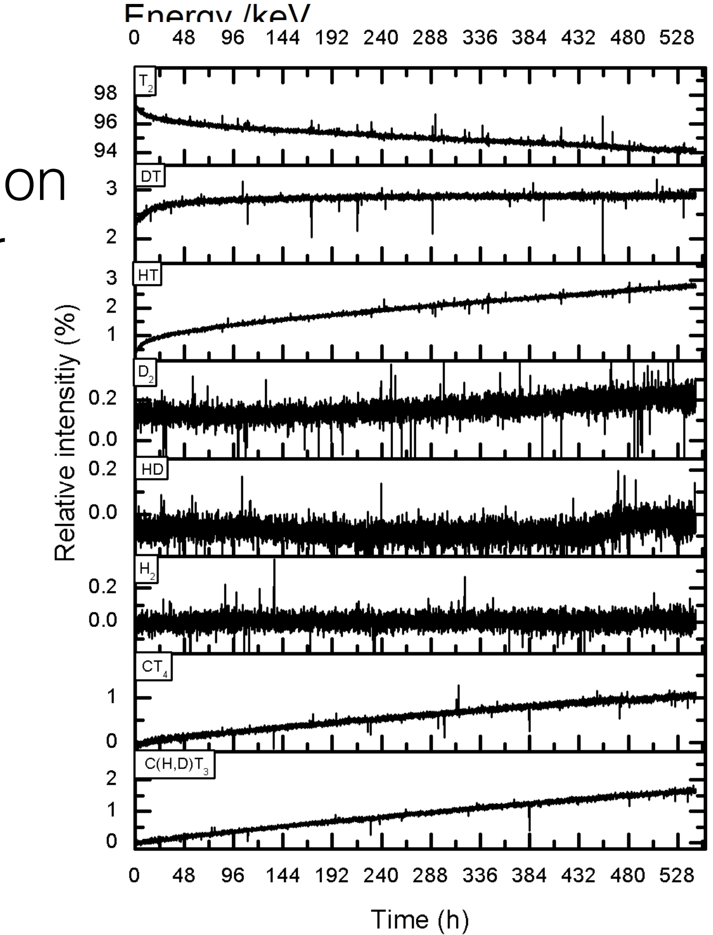
Bremsstrahlung source activity monitor





LNe temperature stability
require 30mK
obtained ~3mK

Raman source composition monitor



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TRIMs will clarify

Angular-selective e-gun will help

exceeded x2

exceeded x10

exceeded x10

exceeded x15

with known source hardware σ = 0.0085 eV²

Conservative design report σ = 0.017 eV²

	Activity	Neutrino mass sensitivity
2015	Commissioning	
2016	Transition to tritium	~1 eV
2017	Running	0.4 eV
2018	Running	0.3 eV
2019	End of run, upgrades?	0.2 eV
2020	Upgrade runs?	

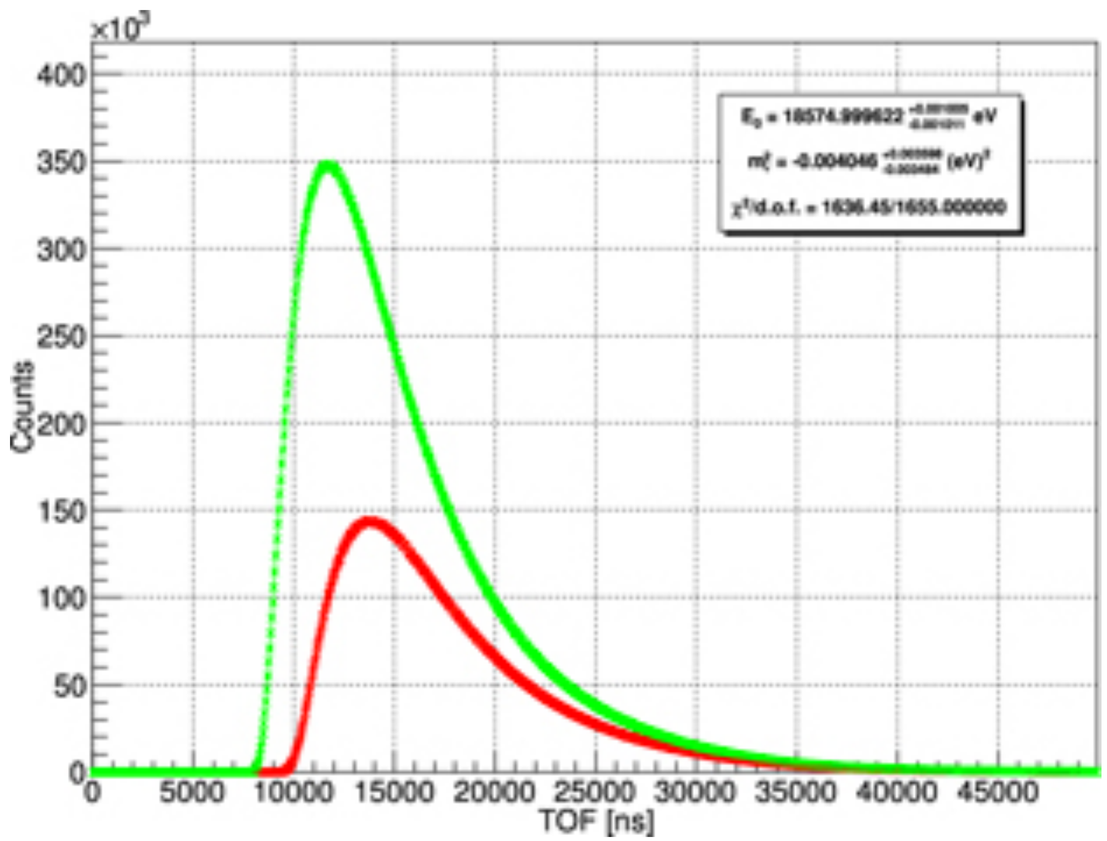
Short version:
KATRIN source and spectrometer should begin science operations in fall 2016.

My prediction is that KATRIN will eventually underperform on statistics but overperform on systematics, which is good.

Future upgrades: TOF

- Steinbrink et al 2013 New J. Phys. 15 113020

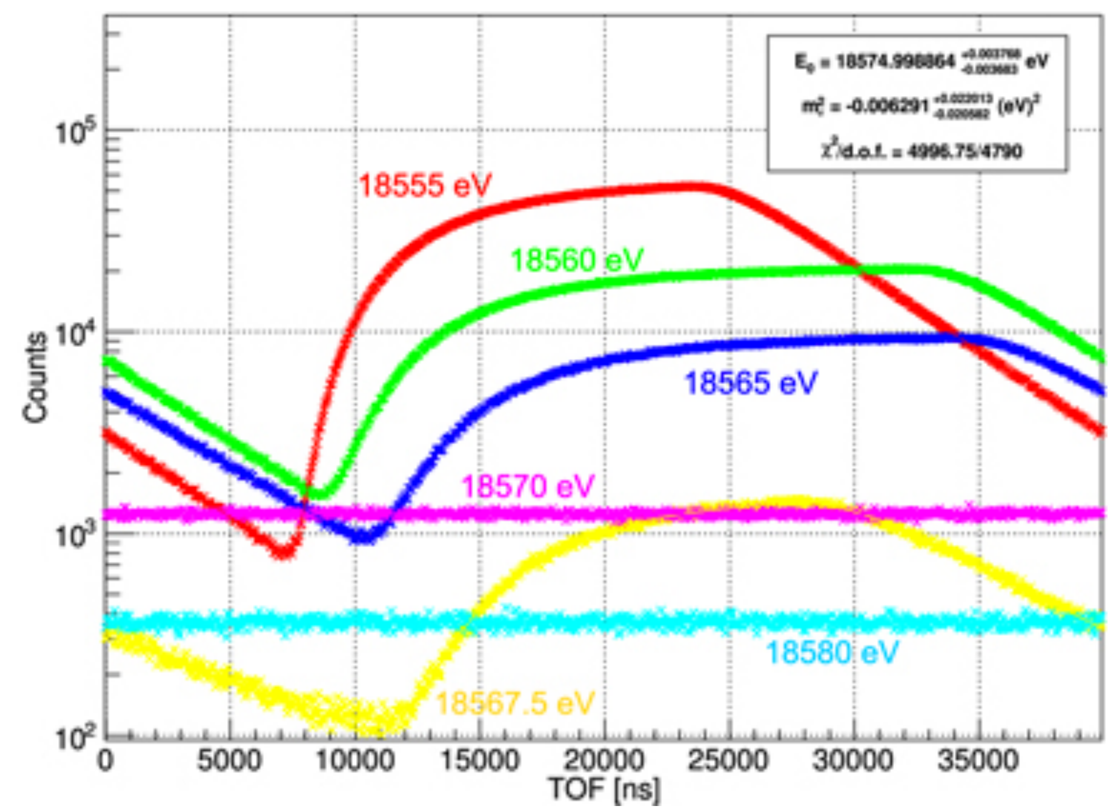
If it's possible to tag electron start time:



push 3y sensitivity to 0.1 eV?

=high-risk R&D? Project 8?

If you "chop" the source every 40μs



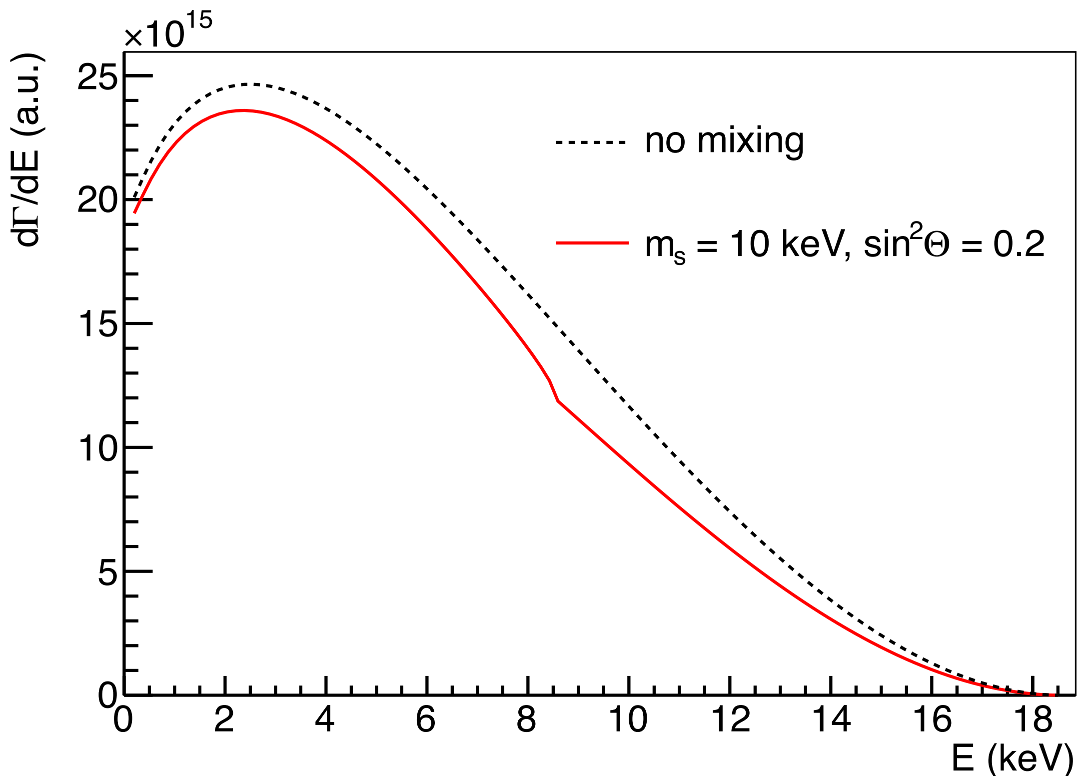
same statistical sensitivity as KATRIN, possible different systematics

= new run mode, needs study

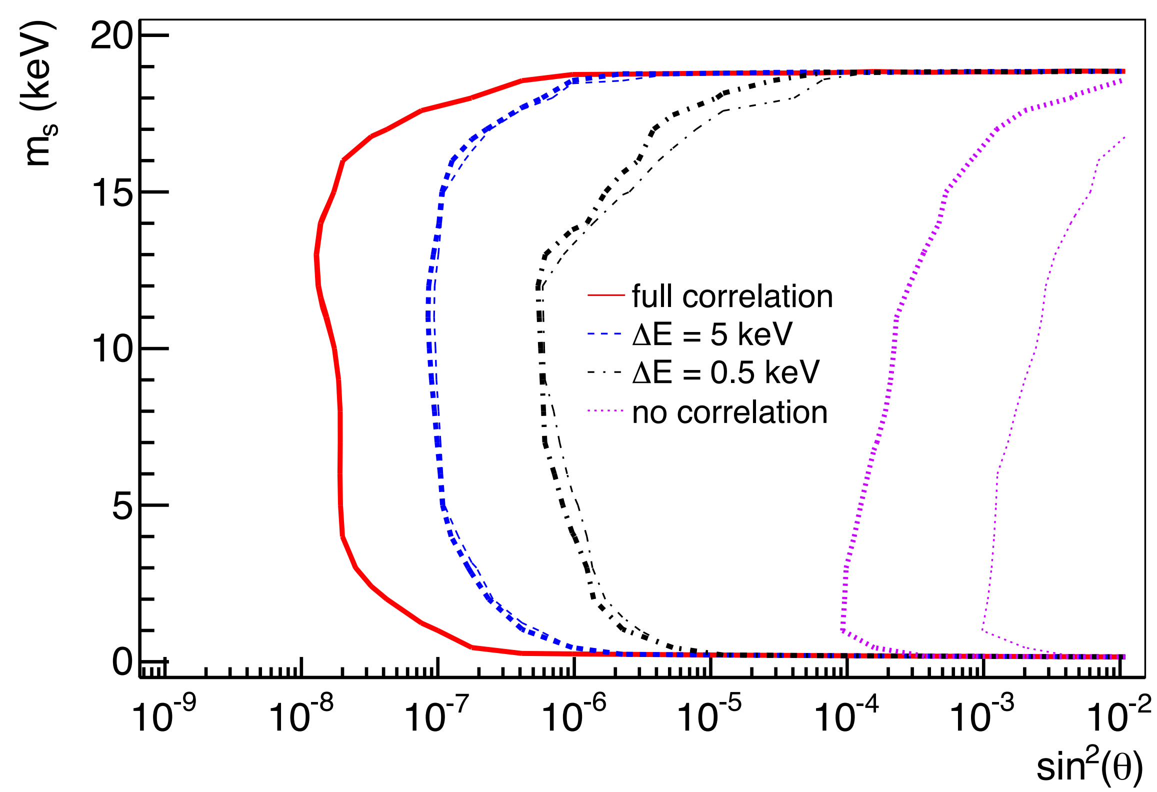
Future upgrades: sterile

Mertens et. al., arXiv:1410.7684

Kink in tritium spectrum due to sterile neutrino



Sterile neutrino sensitivity of dedicated KATRIN run, 3y statistics on full spectrum, realistic systematics



"Full spectrum" = huge count rate (10^{11}/s) at detector.
Needs complete new detector system: large pixel count and fast electronics.

US needs:

- 2015: Detector upgrades, Rear Section commissioning
- 2016—: funding & people for operations

BM & Formaggio, PhysRevD 2009

The Project 8 concept

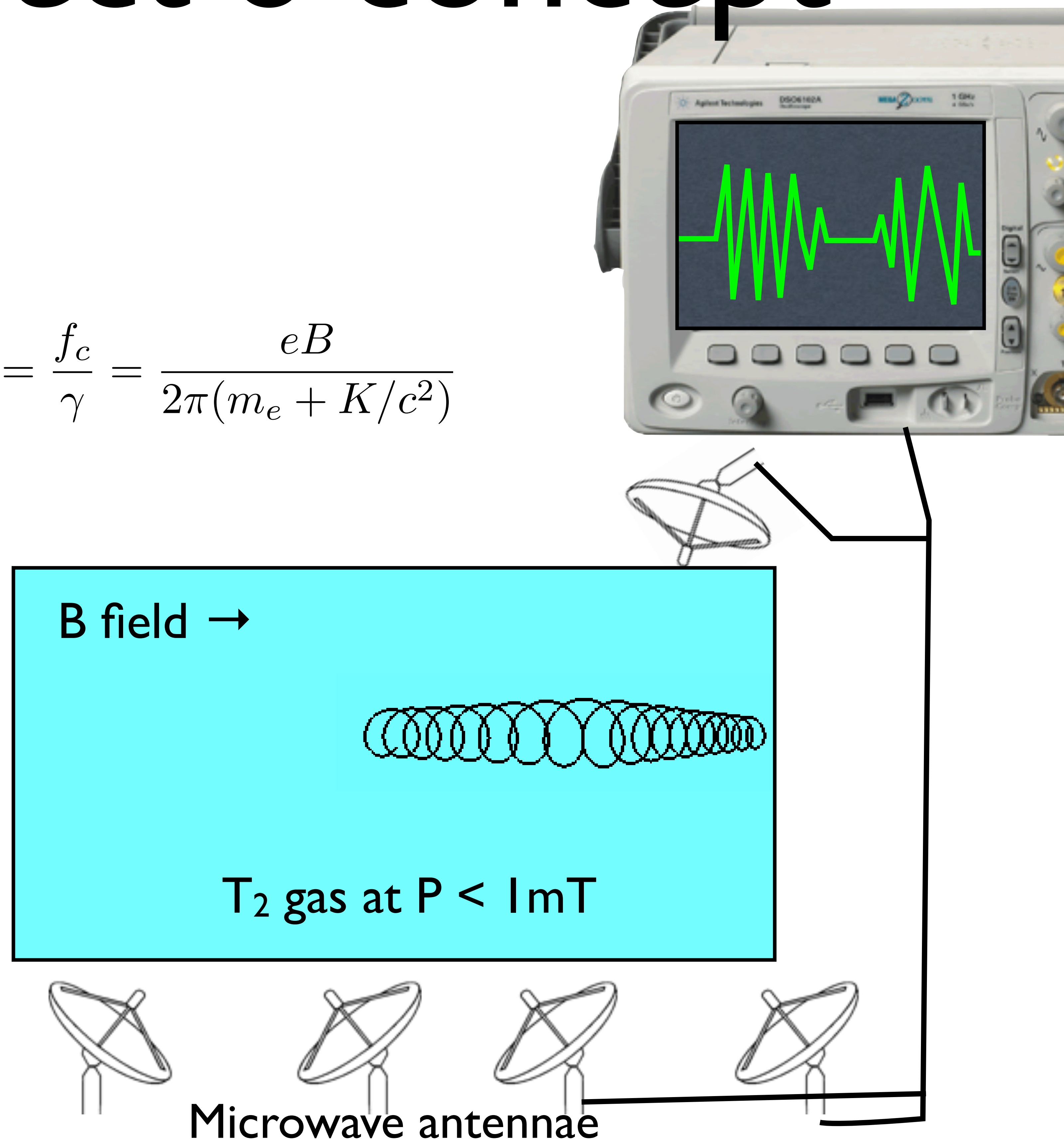
Cyclotron radiation

- emitted by mildly relativistic electrons
- Coherent, narrowband
- 10^{-15} W per electron

$$f_\gamma = \frac{f_c}{\gamma} = \frac{eB}{2\pi(m_e + K/c^2)}$$

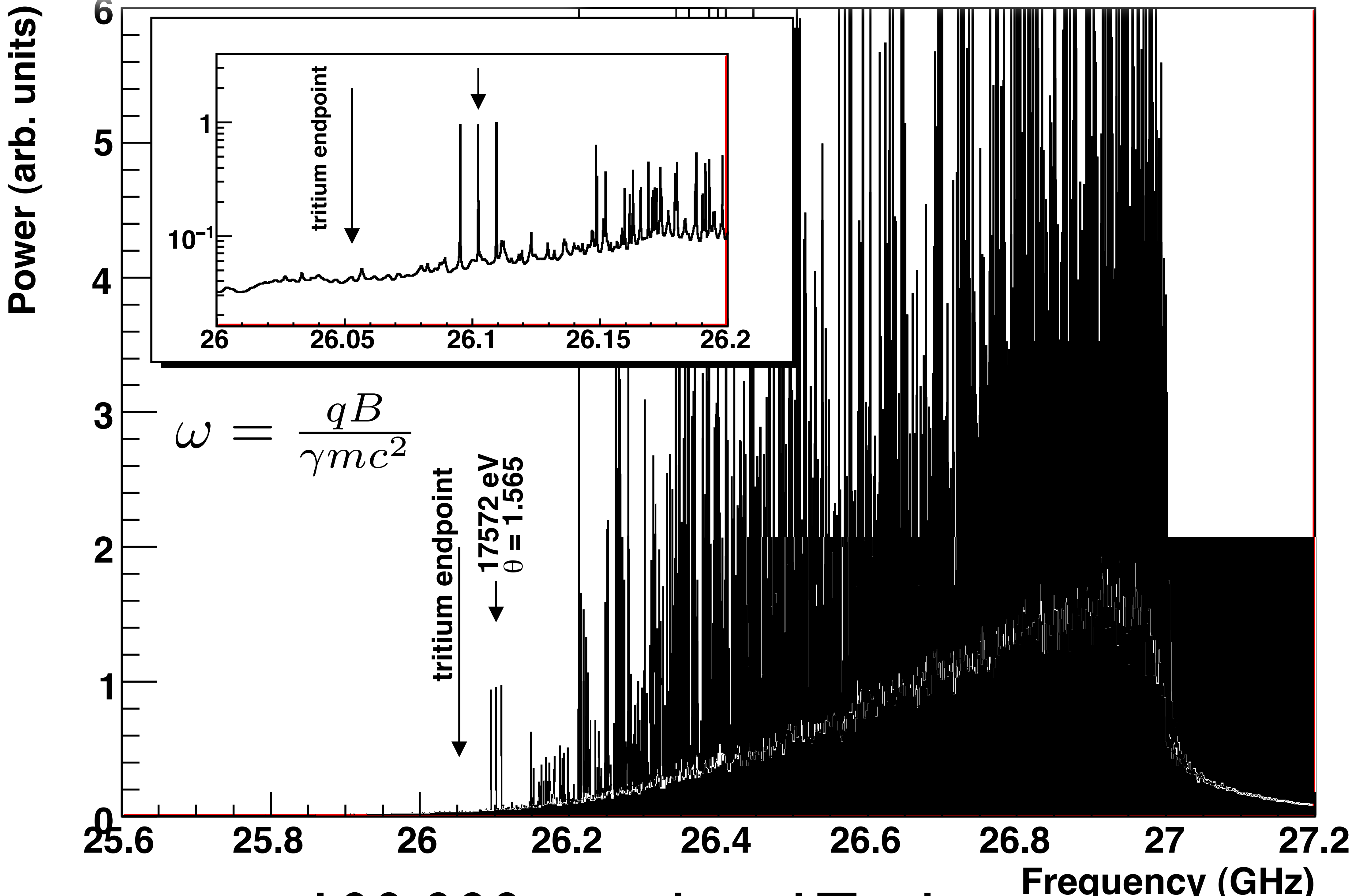
$$P_{\text{tot}} = \frac{1}{4\pi\epsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta_\perp^2}{1-\beta^2}$$

- Electron energy contributes to velocity v, power P, frequency ω
  - *Can we detect this radiation, measure v, P, ω, and determine* E ± 1 eV?



rare high-energy electrons

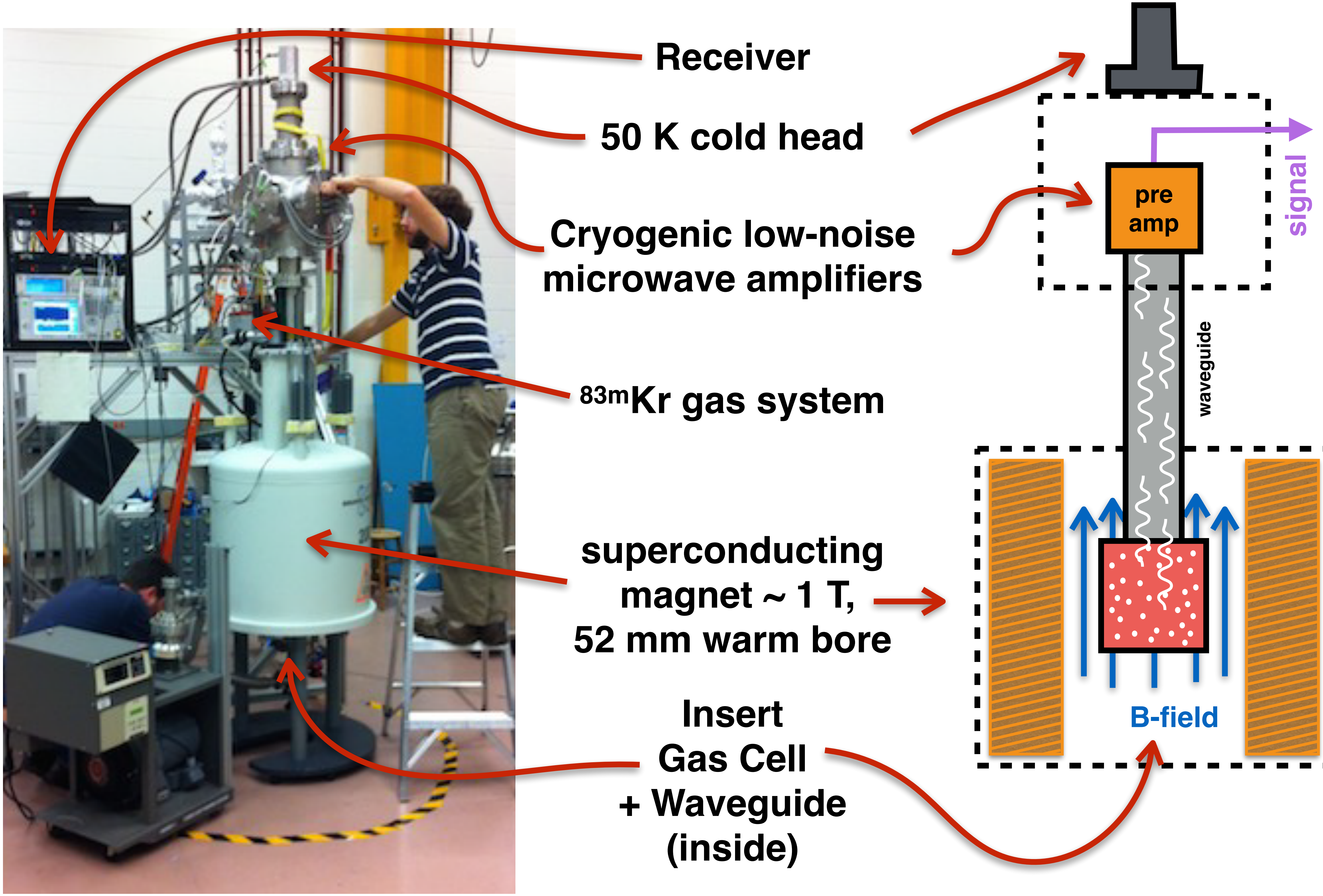
many overlapping low-energy electrons



$$\omega = \frac{qB}{\gamma mc^2}$$

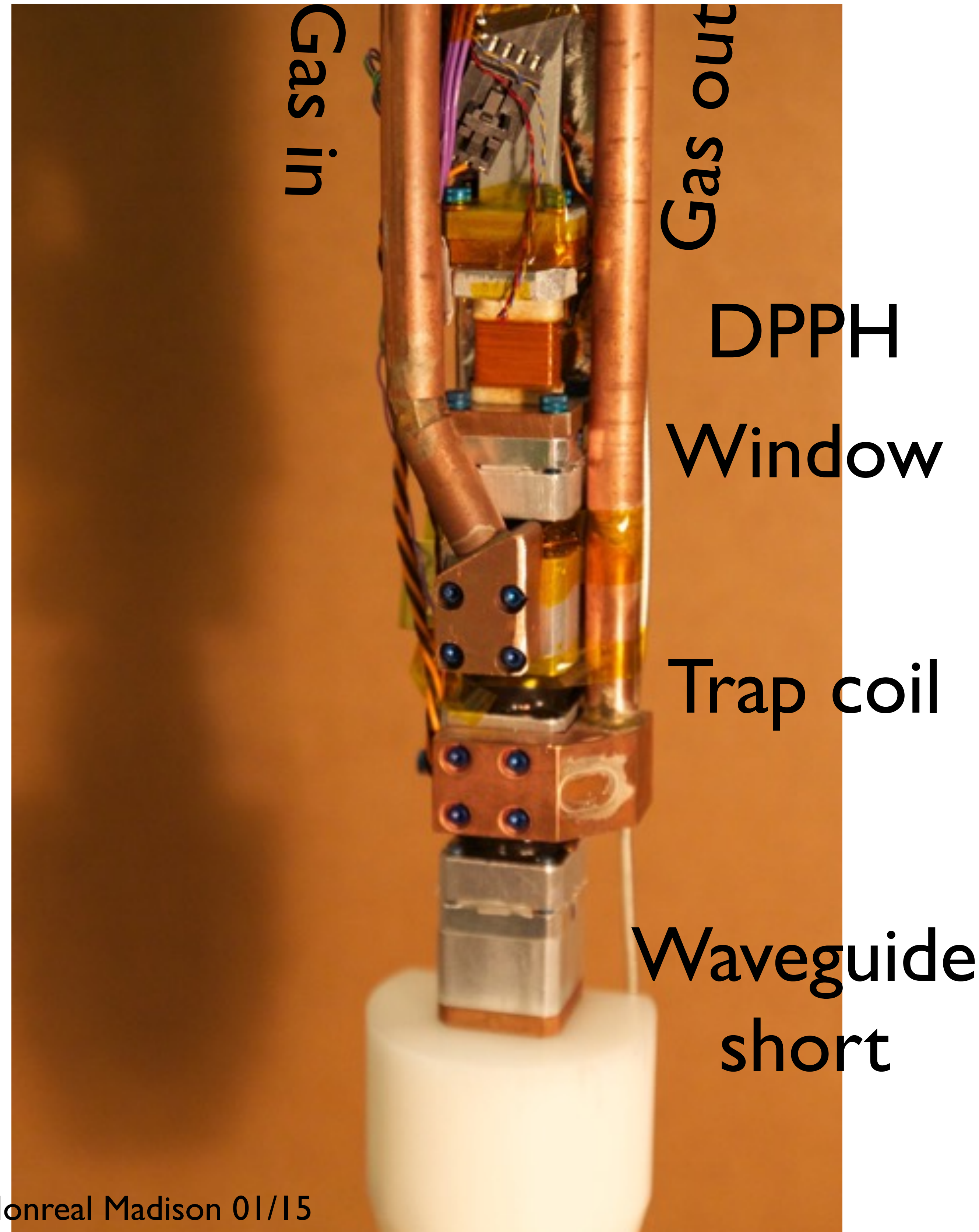
BM & Formaggio, PhysRevD 2009

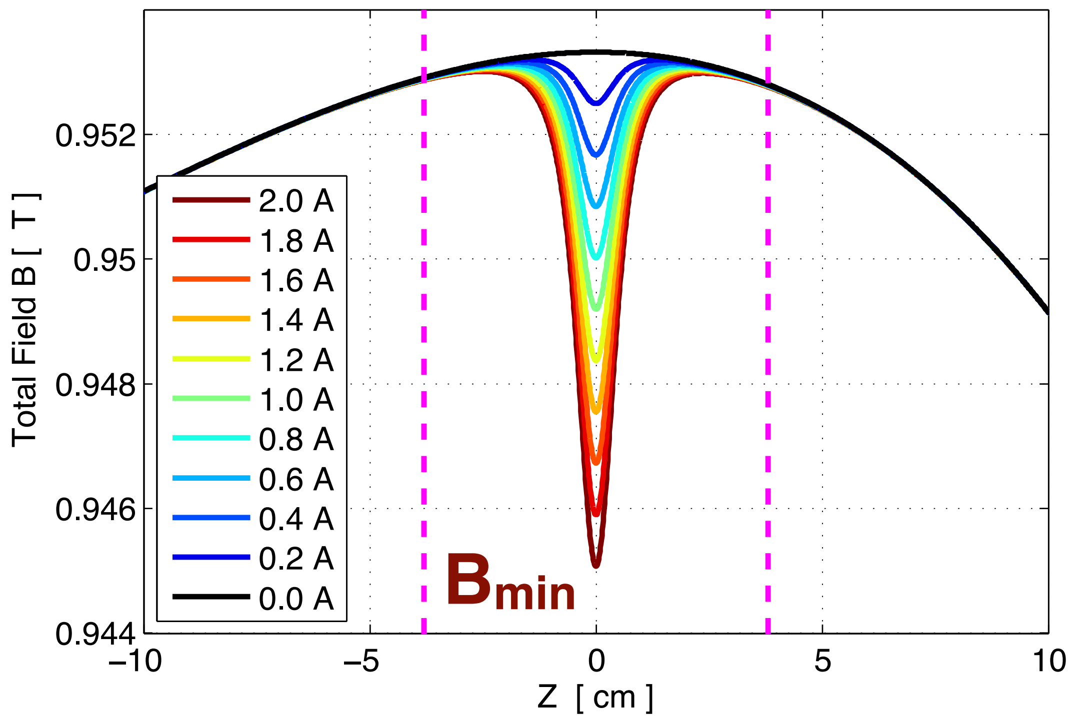
100,000 simulated T_2 decays



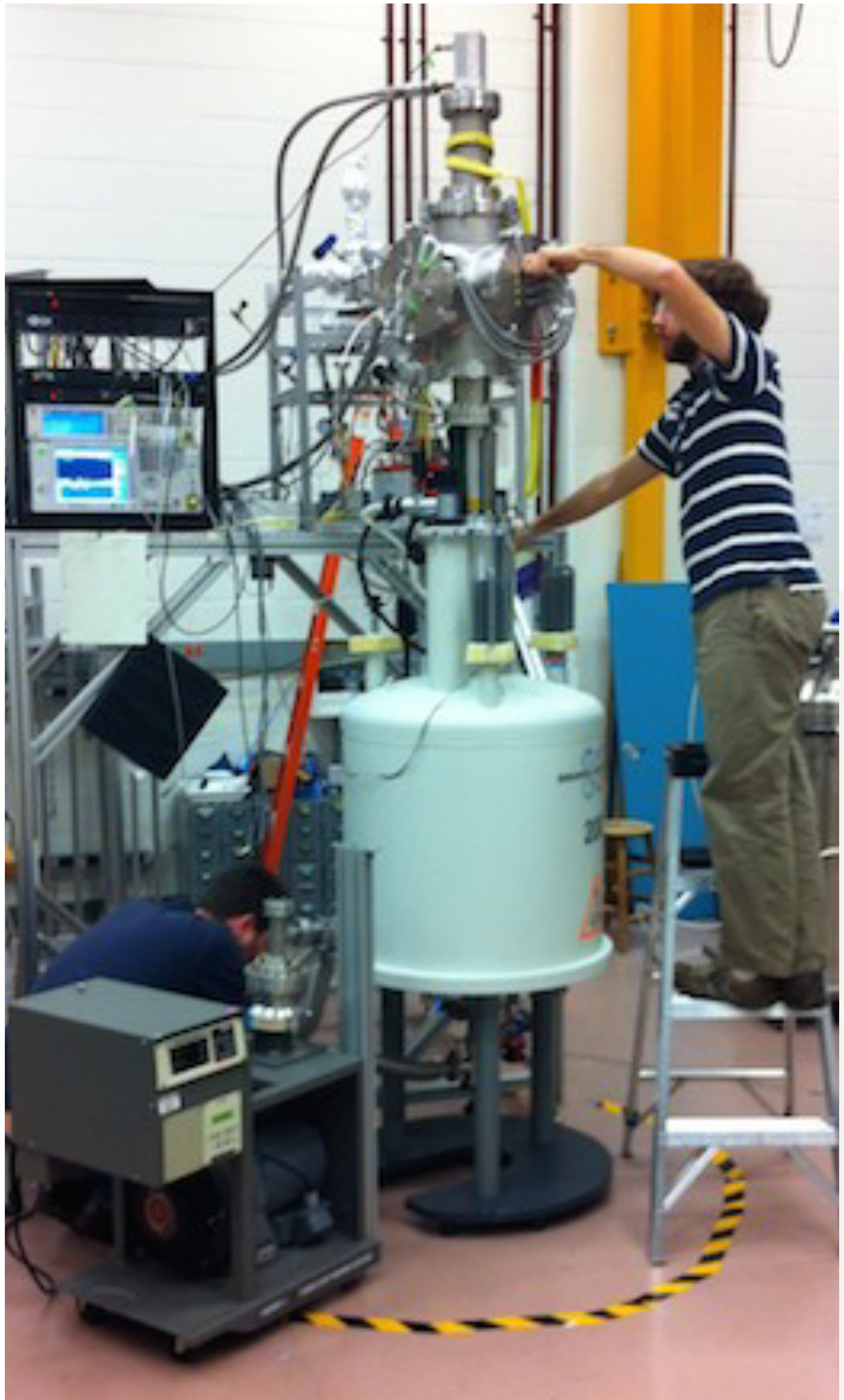
Receiver
50 K cold head
Cryogenic low-noise microwave amplifiers
^{83m}Kr gas system
superconducting magnet ~ 1 T, 52 mm warm bore
Insert Gas Cell + Waveguide (inside)
pre amp
signal
waveguide
B-field

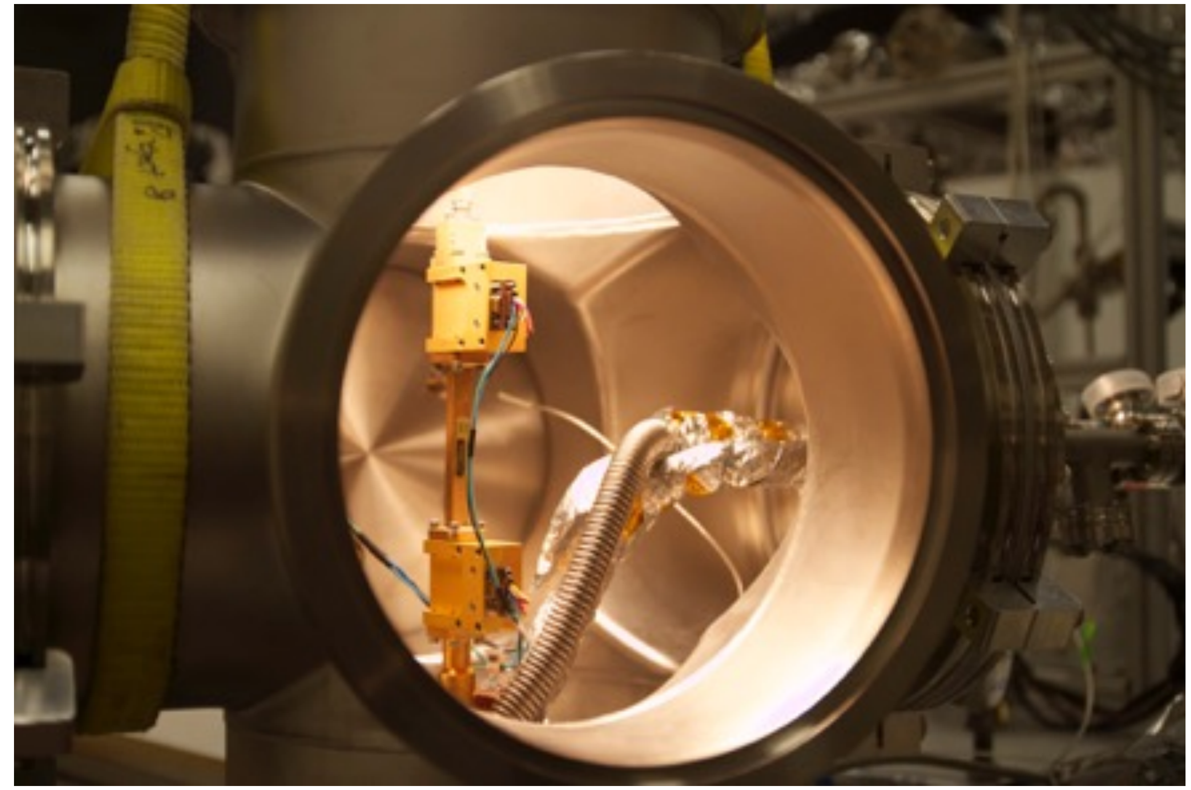
Waveguide cell

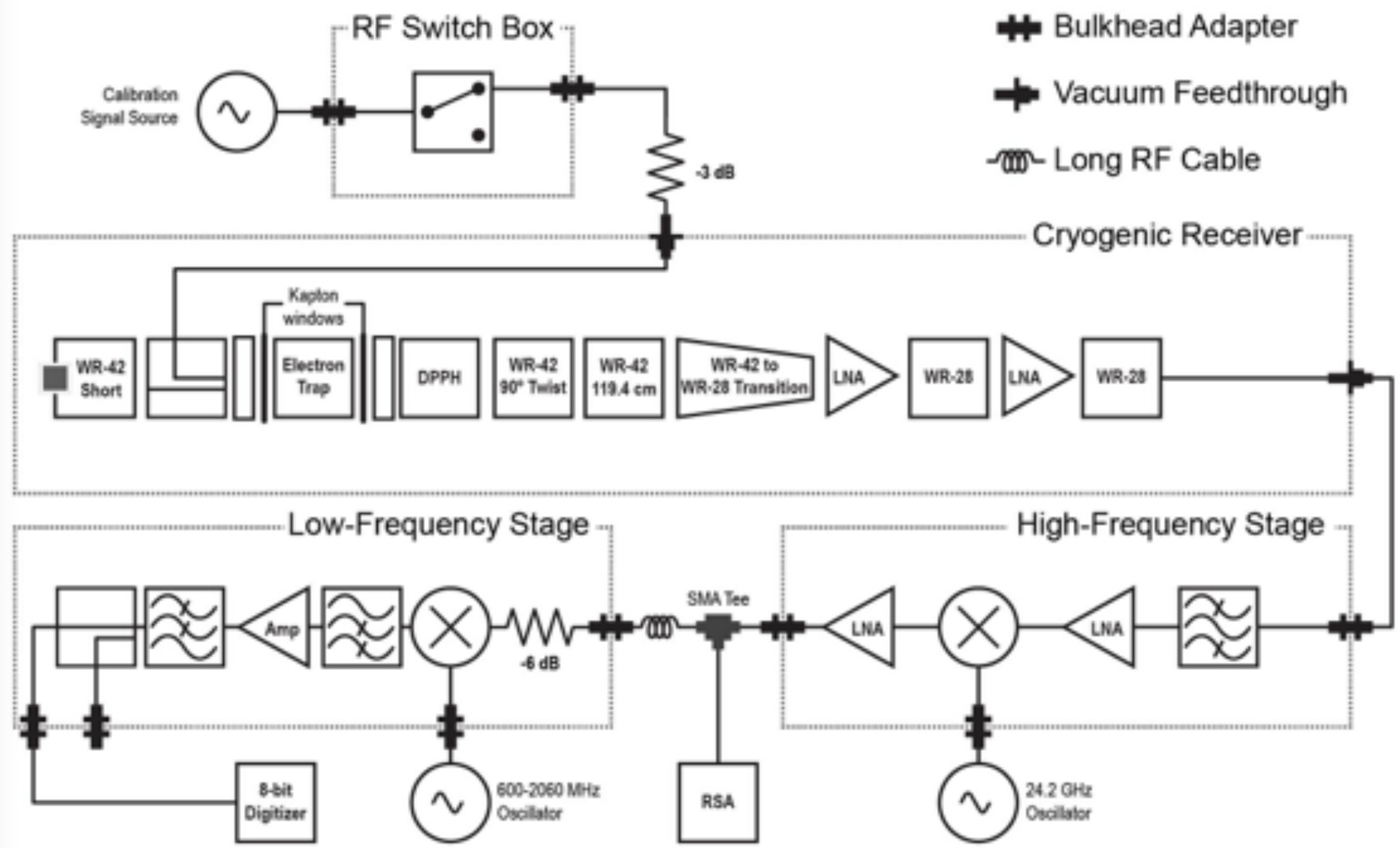




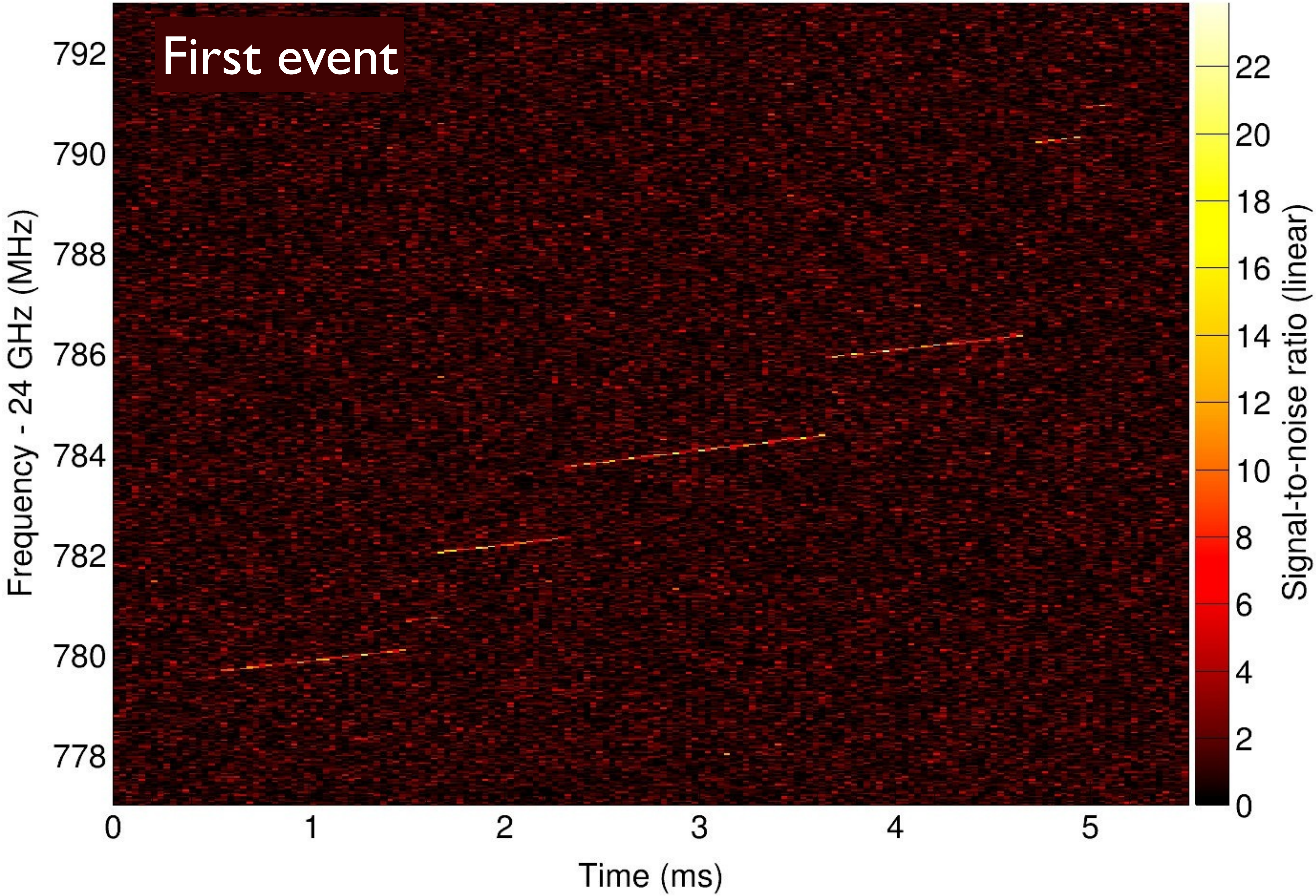
RF chain and reciever

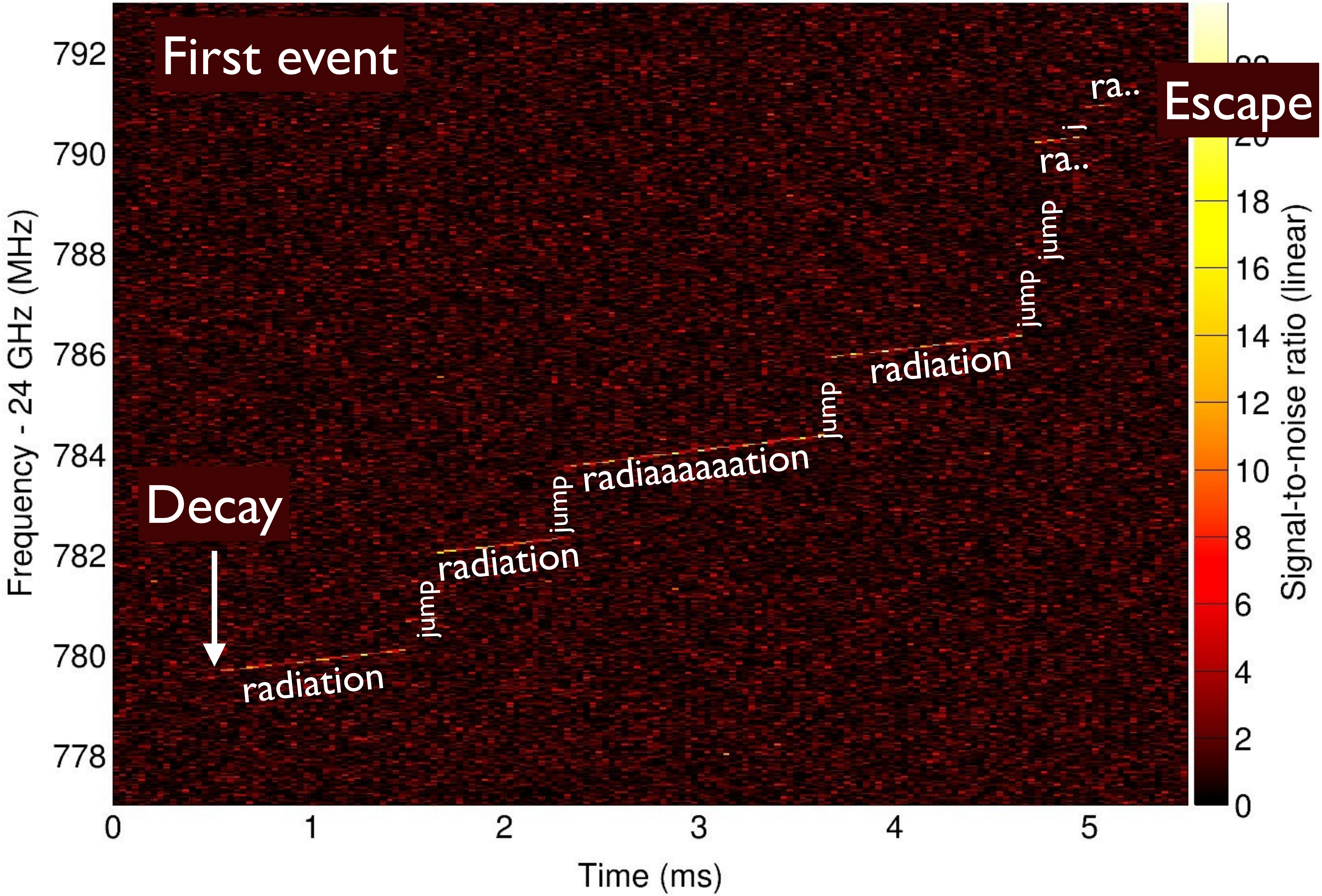


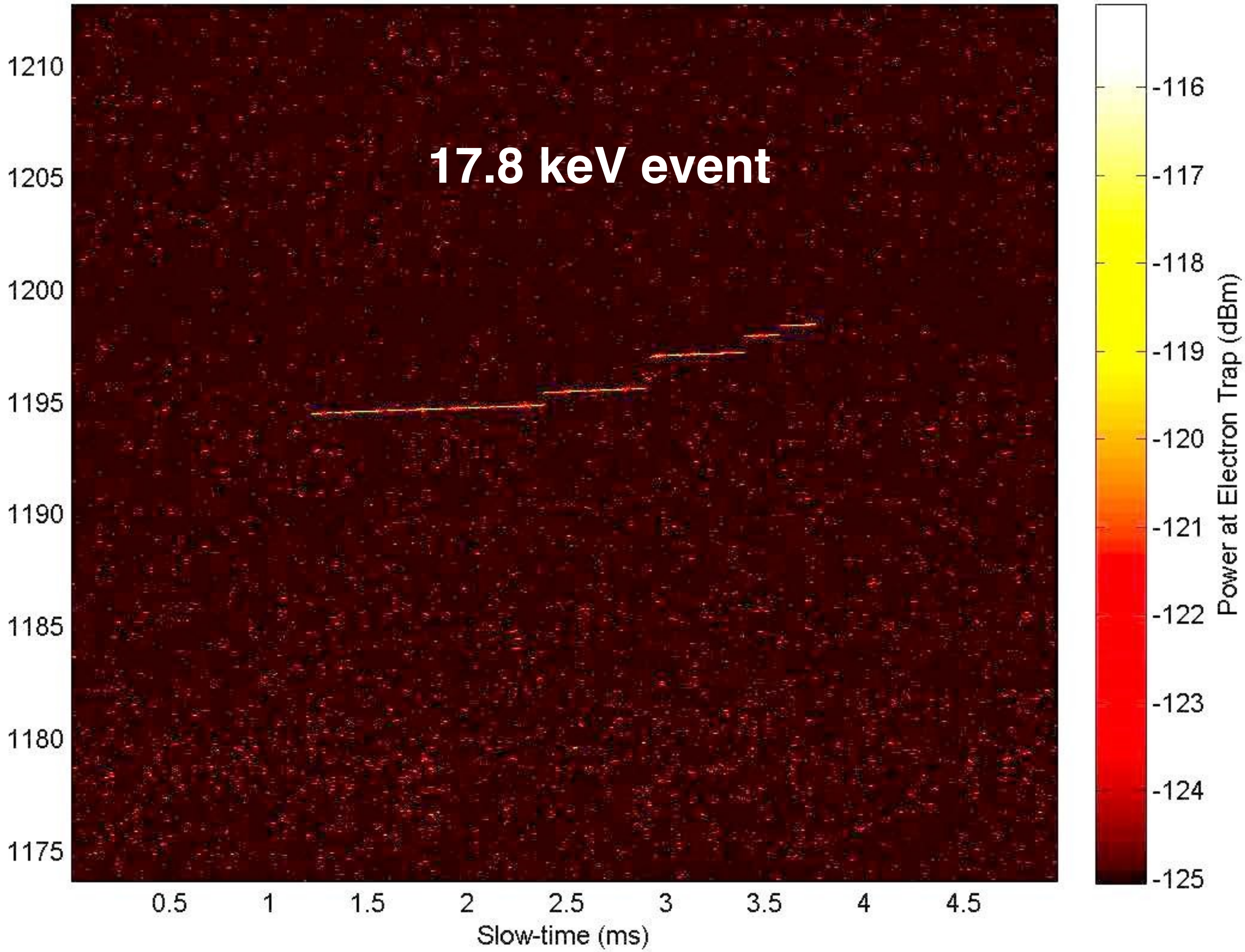




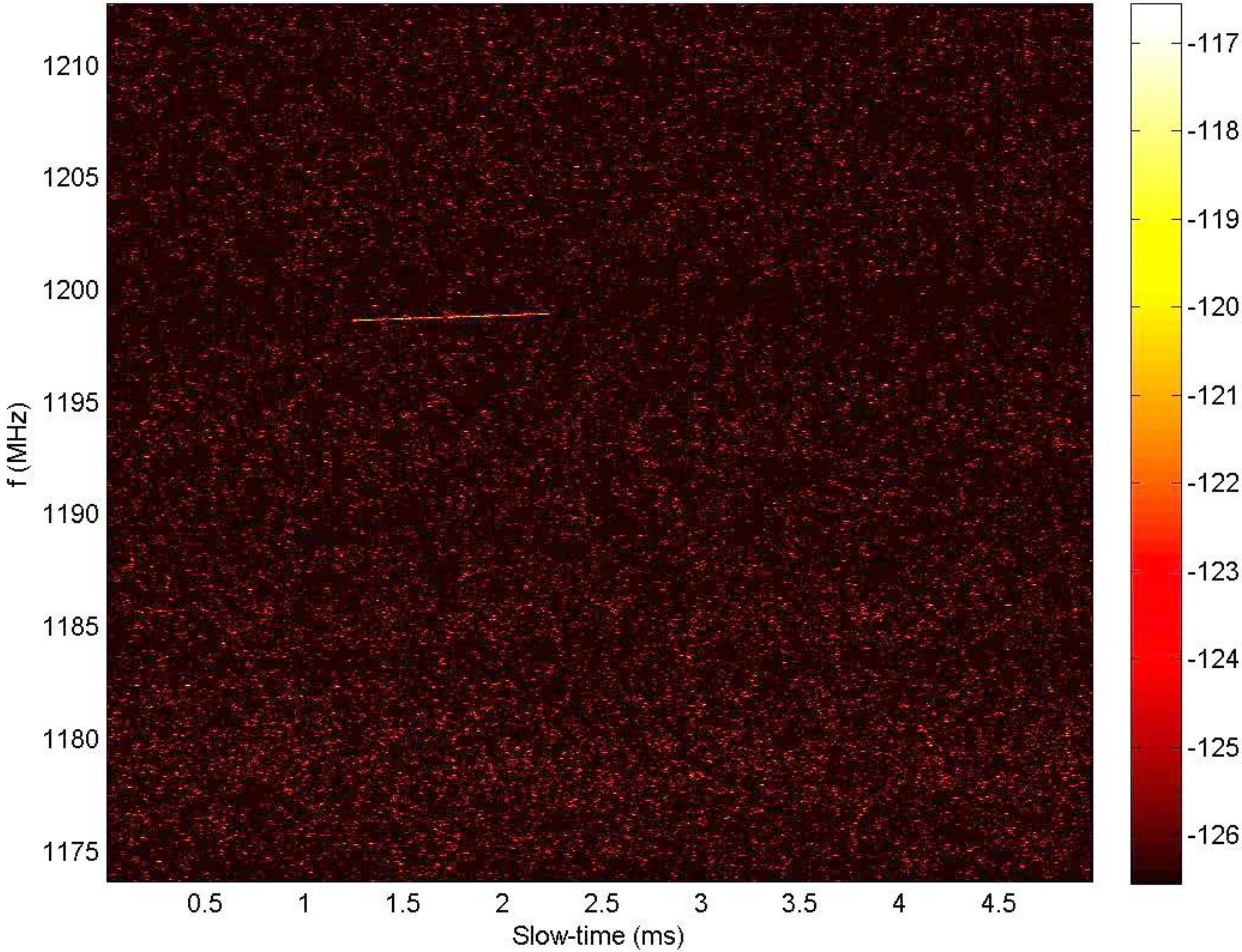
Asner et. al., arxiv:1408.5362, PRL in review



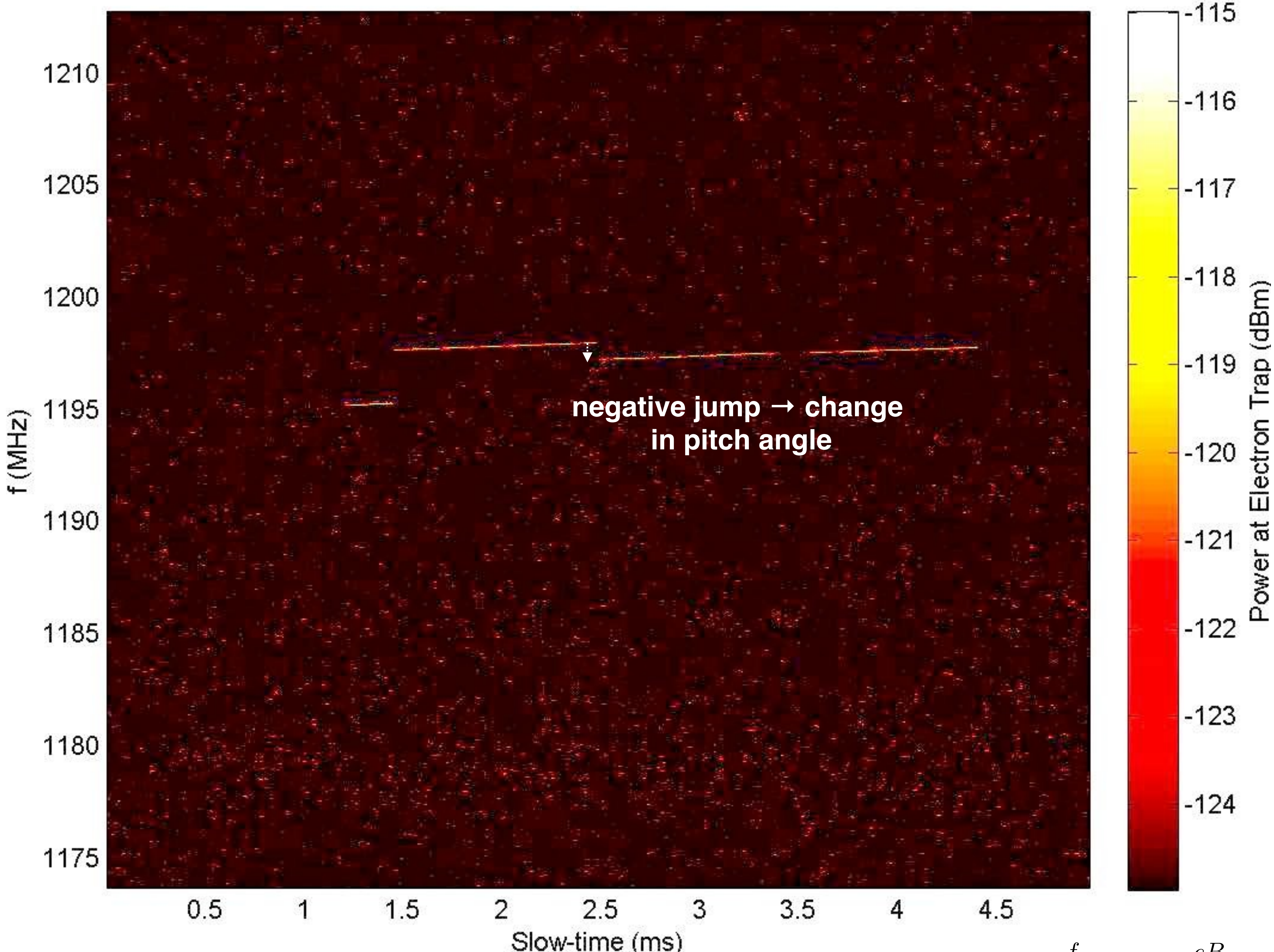

First event
Escape
Decay
radiation
jump
radiation
jump
radiaaaaaation
jump
radiation
jump
jump
ra..
j
ra..
Frequency - 24 GHz (MHz)
778
780
782
784
786
788
790
792
Time (ms)
0
1
2
3
4
5
Signal-to-noise ratio (linear)
0
2
4
6
8
10
12
14
16
18



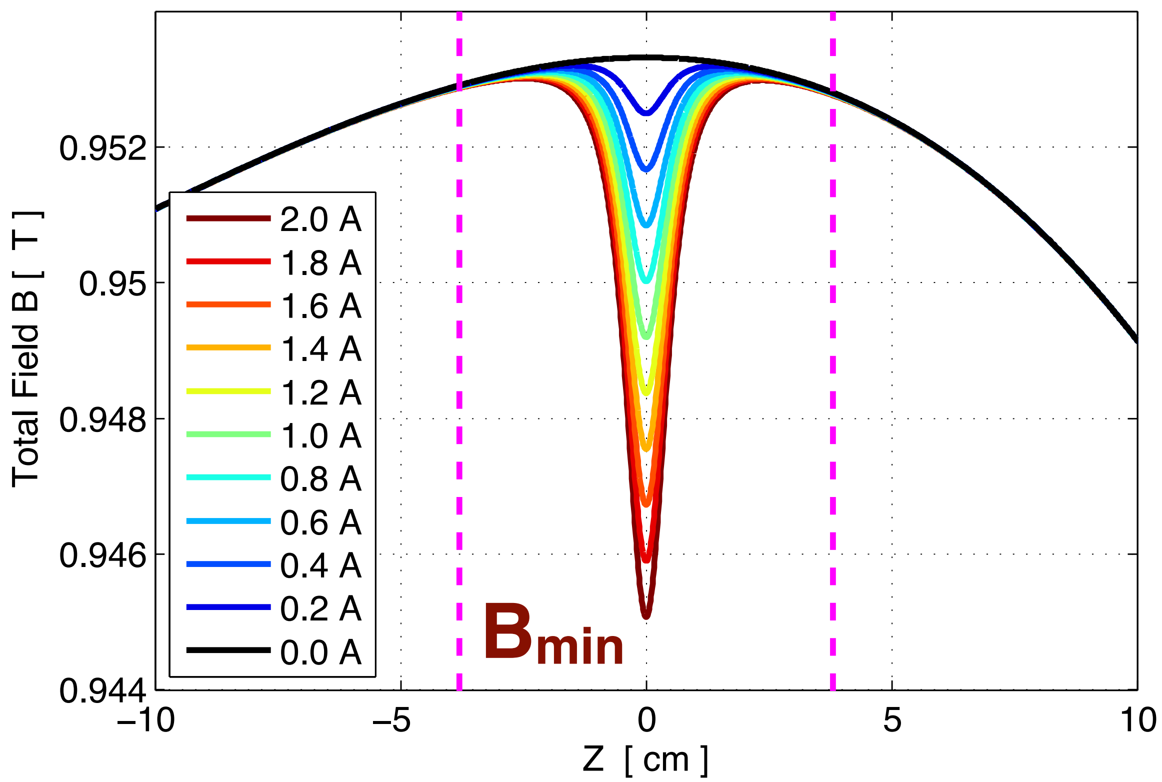
17.8 keV event
1210
1205
1200
1195
1190
1185
1180
1175
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Slow-time (ms)
-116
-117
-118
-119
-120
-121
-122
-123
-124
-125
Power at Electron Trap (dBm)

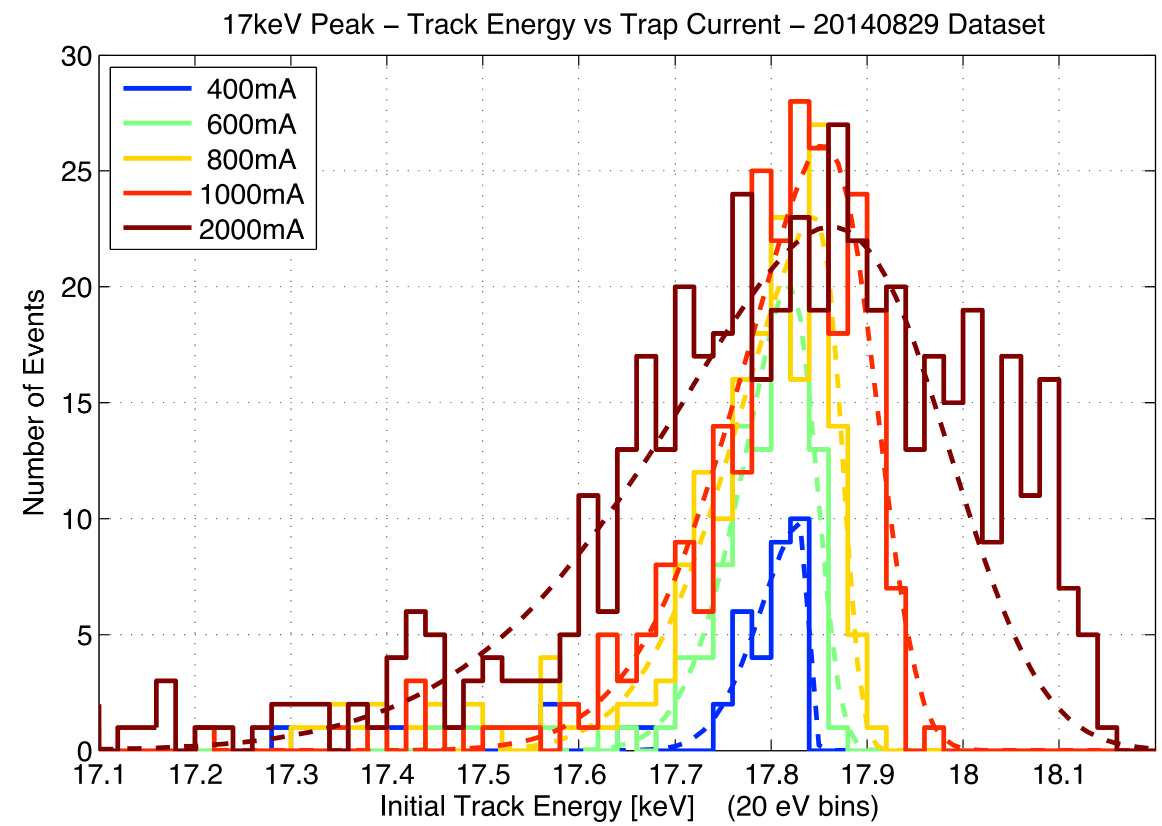


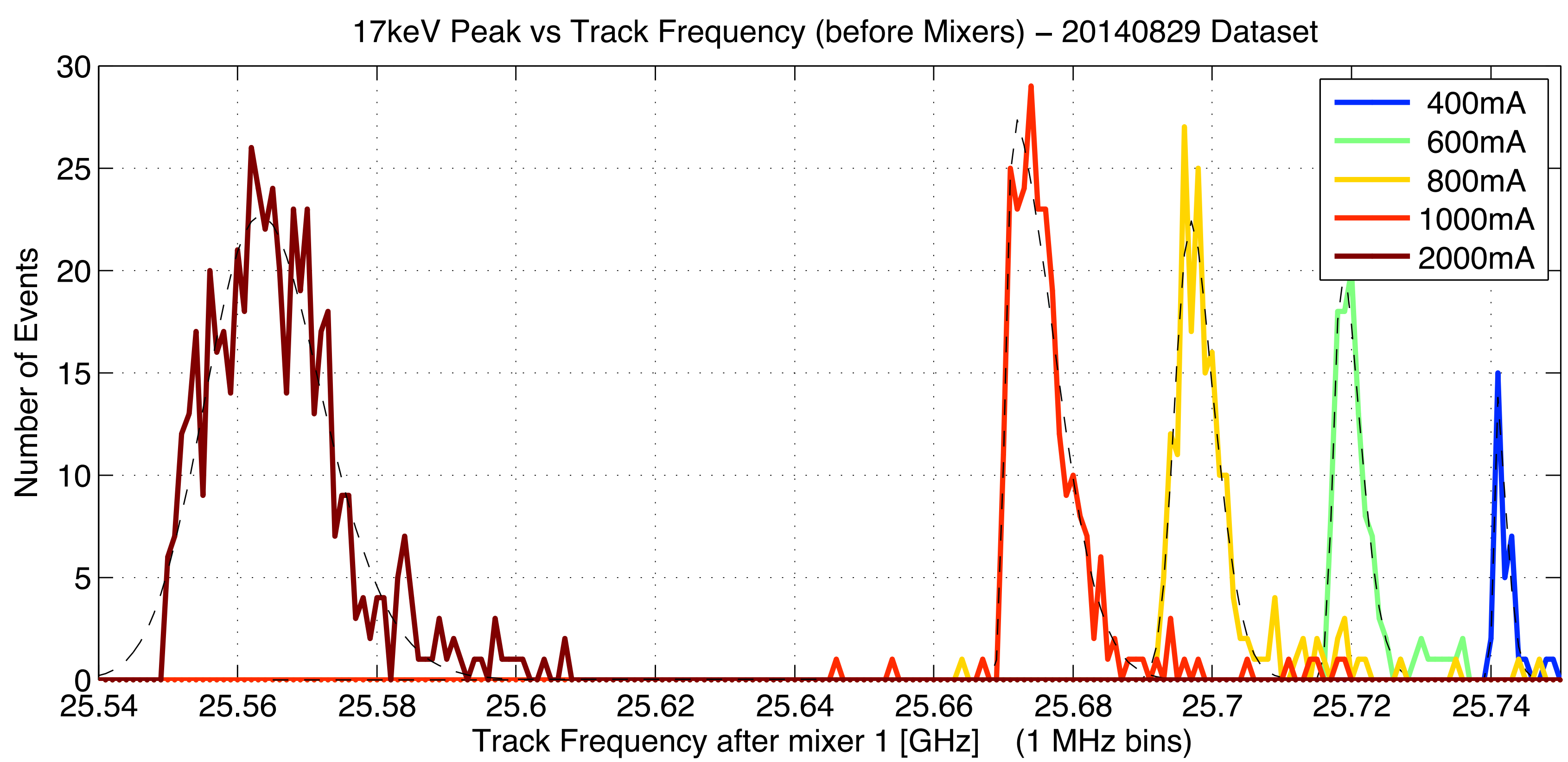
1210
1205
1200
1195
1190
1185
1180
1175
f (MHz)
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Slow-time (ms)
-117
-118
-119
-120
-121
-122
-123
-124
-125
-126



$f_{\sim} = \frac{f_c}{} = \frac{eB}{}$







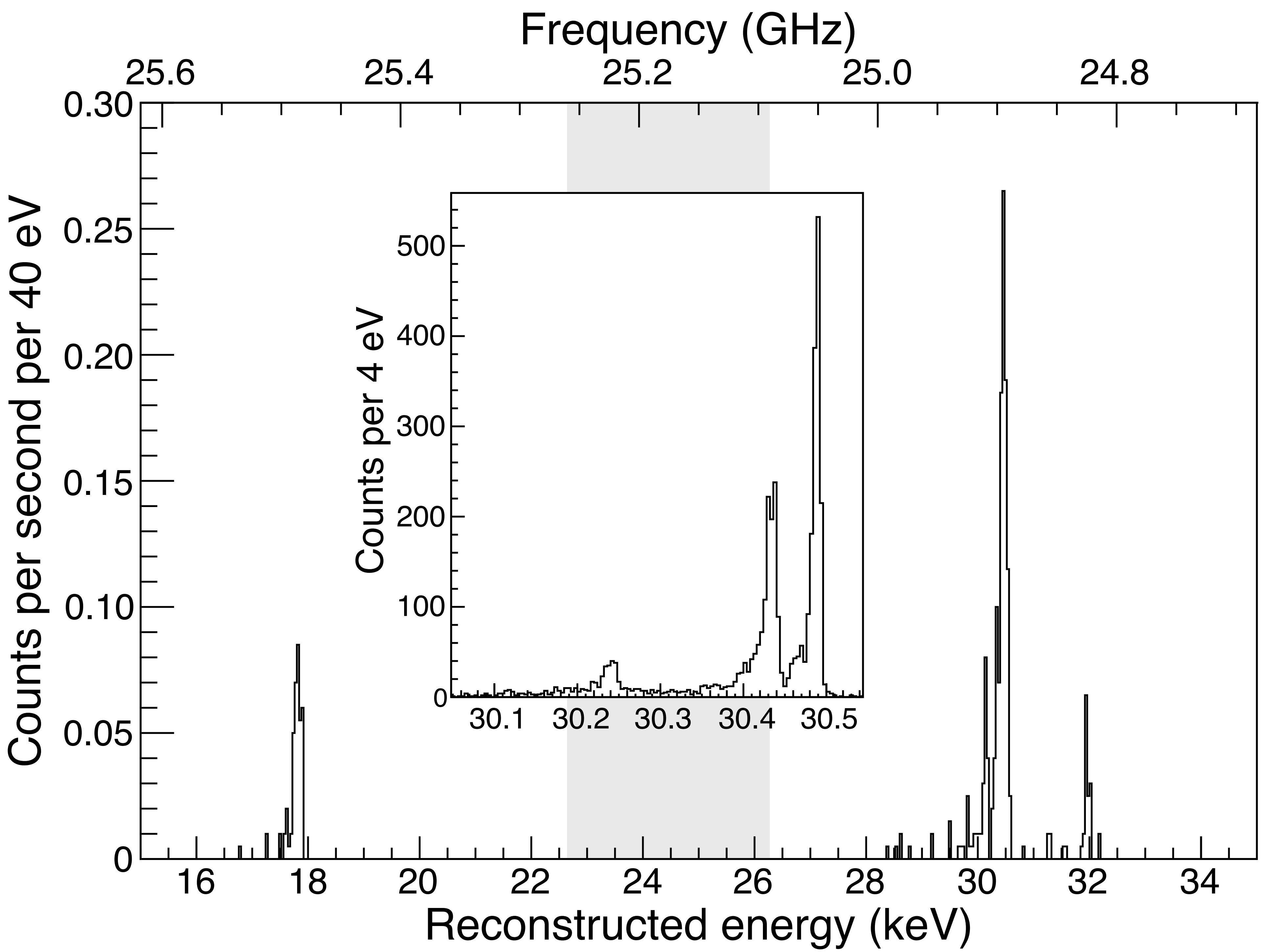
First run:
σ_E = 100 eV

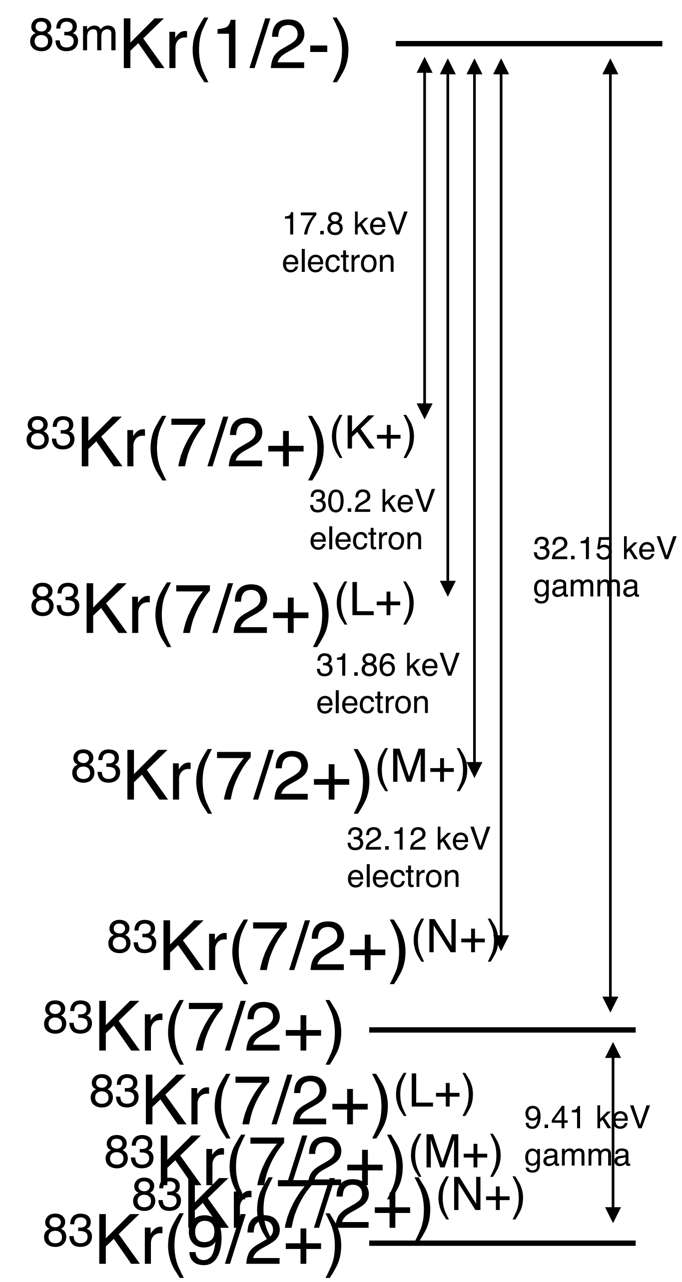
Best obtained so far: σ_E = 10 eV

Not a fundamental limit! New runs will have more-uniform B field in trap.

^{83m}Kr conversion electron spectrum

Asner et. al., arXiv:1408.5362 PRL in review

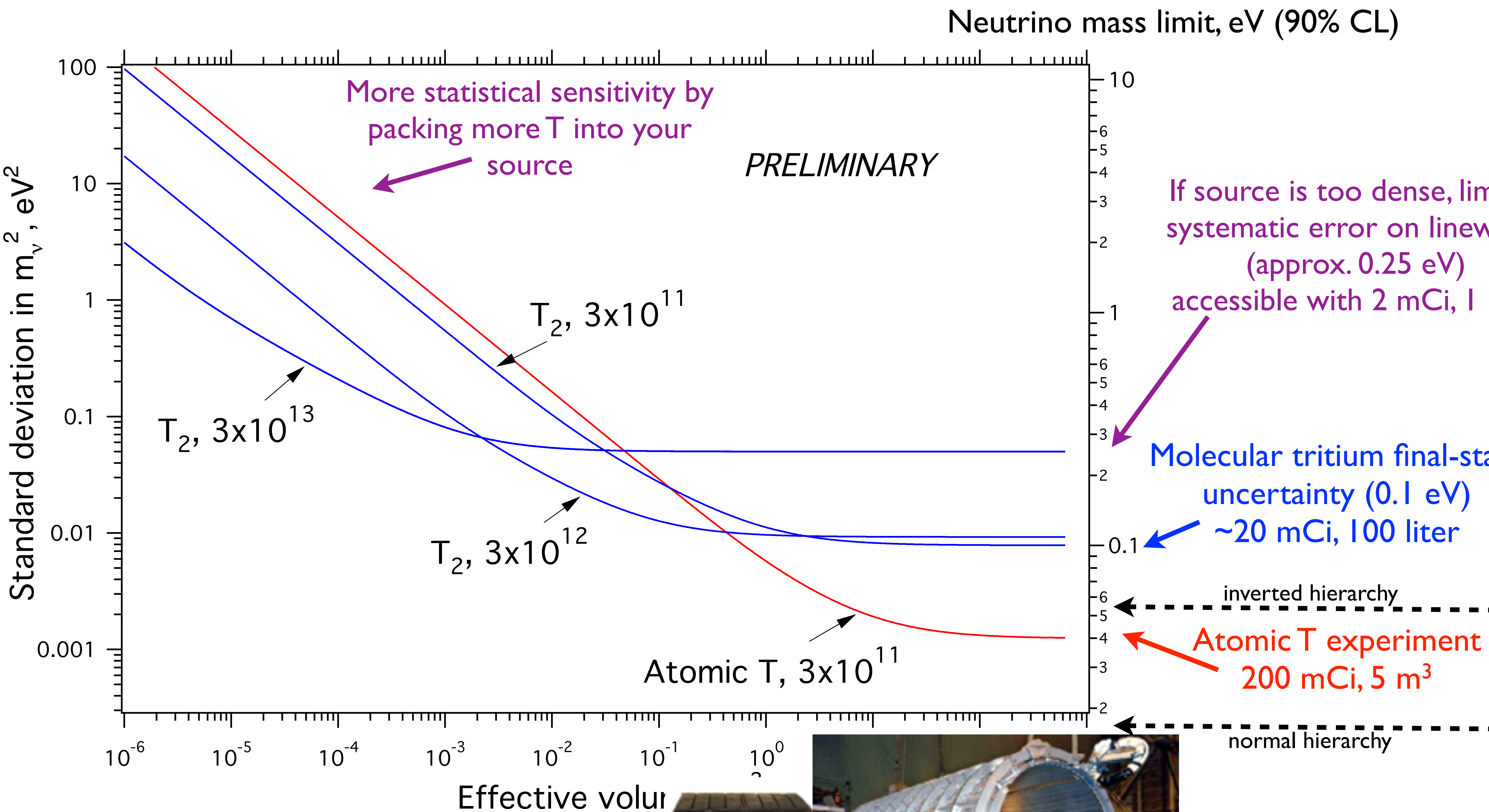


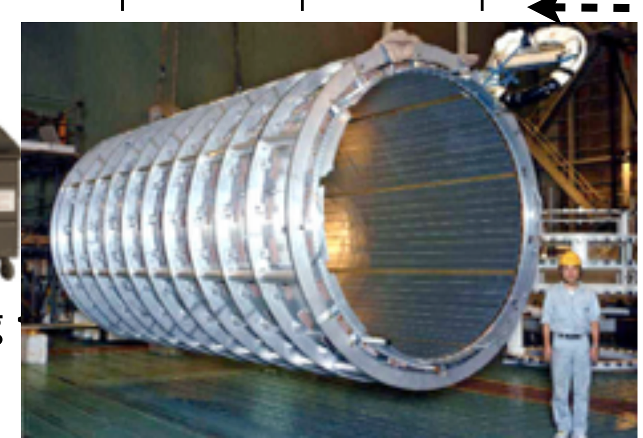


K-conversion L-conversion M,N

Project 8 sensitivity estimates:

Small and high-density or large and low-density?

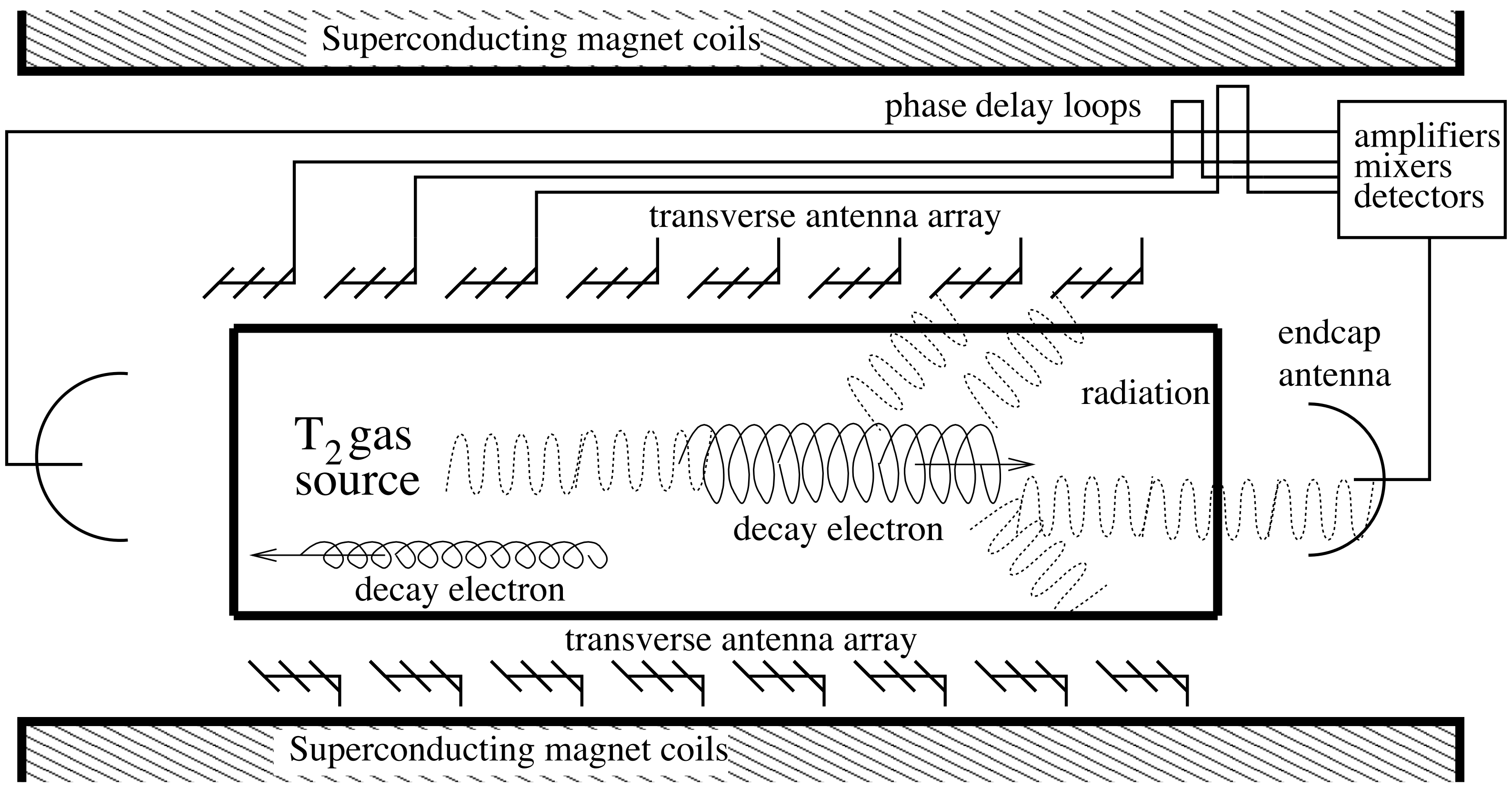




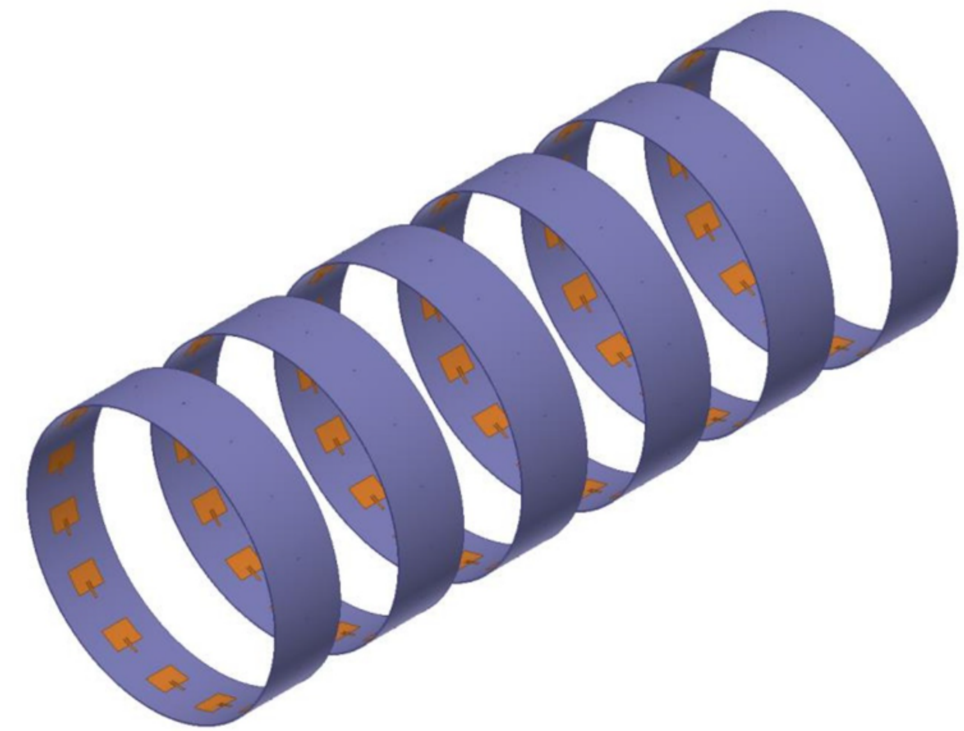
Details: B=1 Tesla, background = 1 μHz/eV, livetim
pressure broadening known to 1%, field broadening

P8 in large volumes

Cartoon from BM & JF 2009

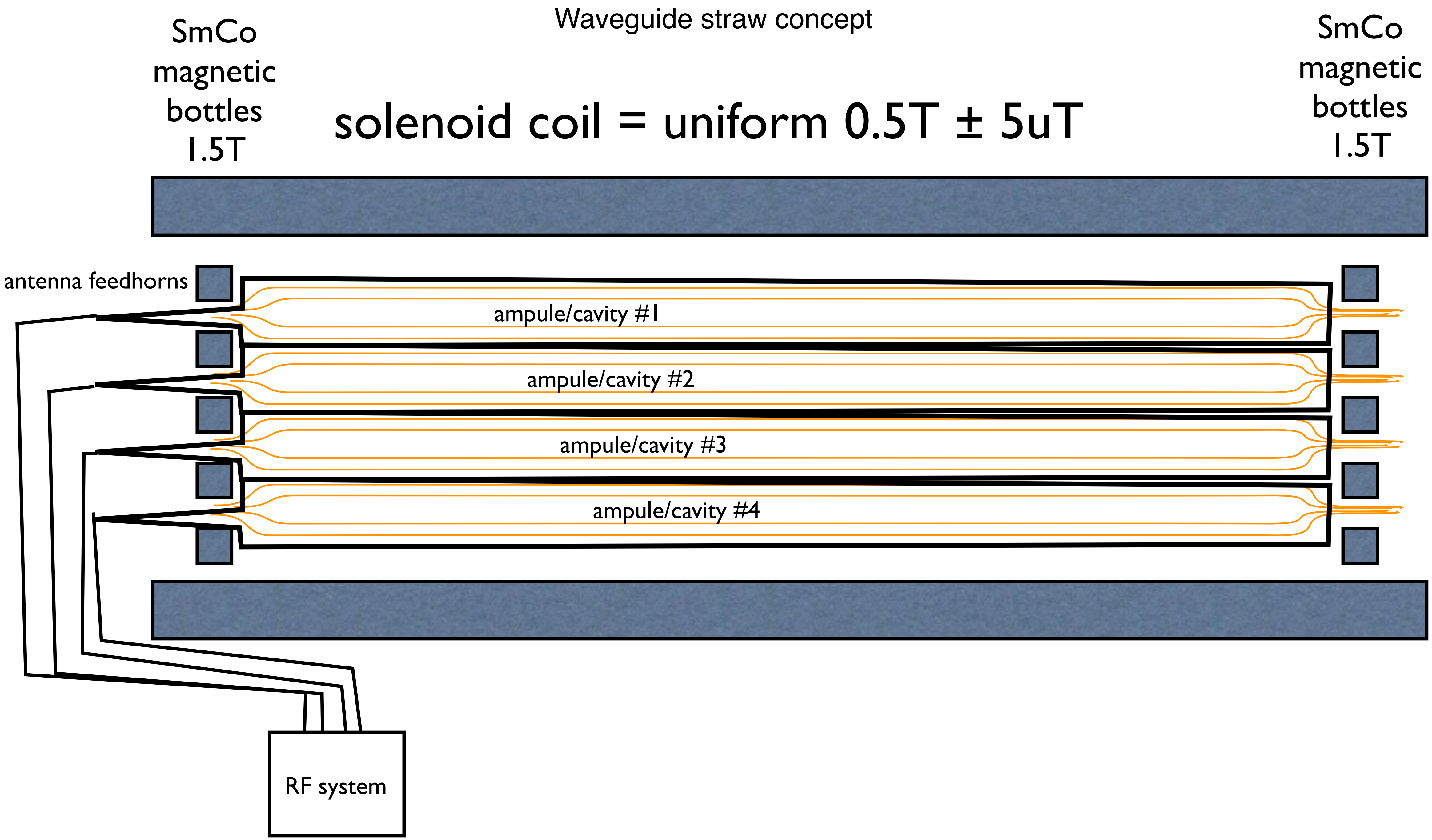


Mark Jones, PNNL design



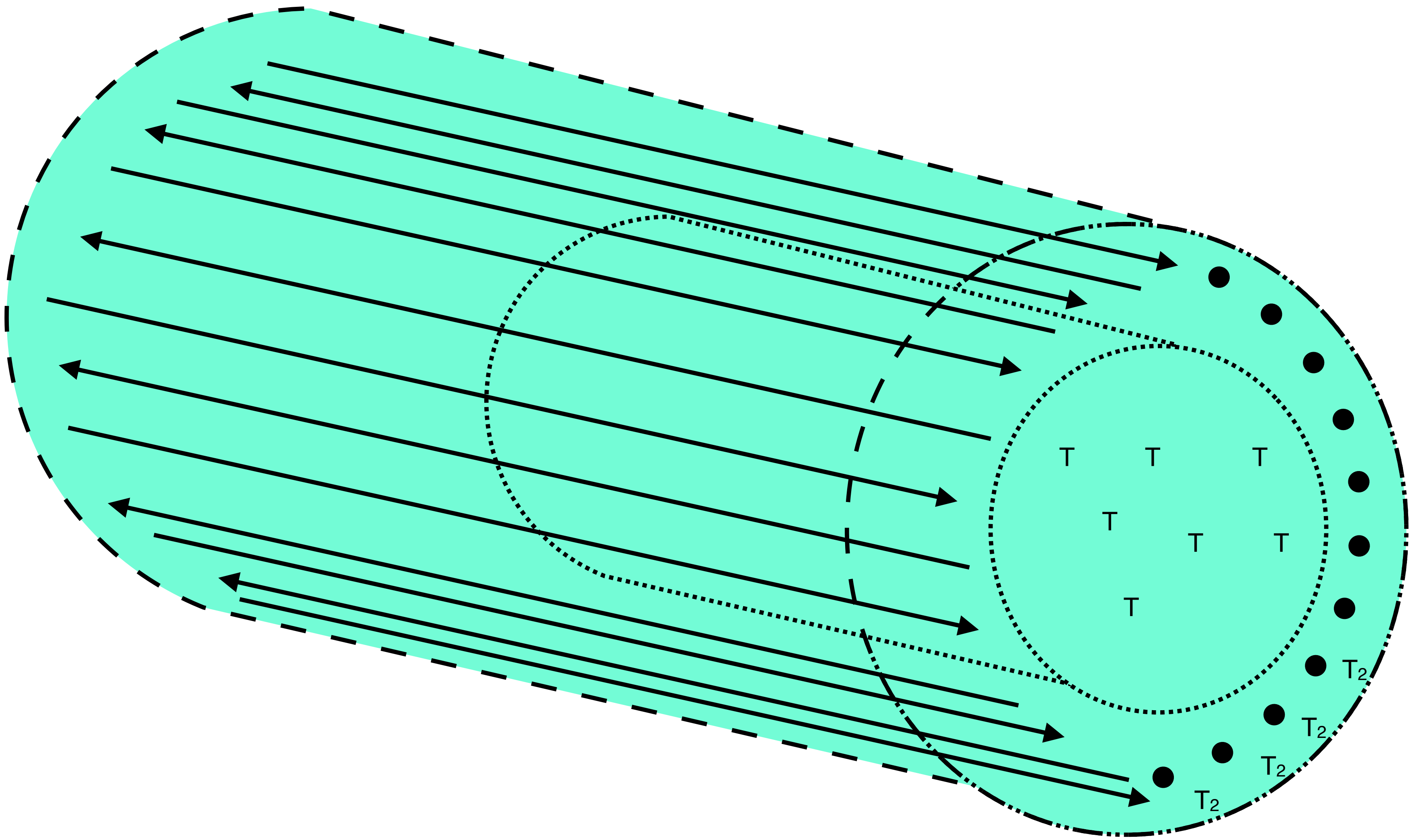
patch antenna configuration

P8 in large volumes



Early ideas for atomic T

Goal: remove 0.3 eV smearing of spectrum due to THe ion final states
Remove systematic uncertainty on that smearing
Challenge: need extremely low T_2 fraction



- Dissociate T_2 gas
- Inject into multi-cusp Ioffe trap
- T atoms retained (t=?) in trap interior
- T_2 freezes to cold walls
- ^{3}He buffer gas cooling?
- B field uniformity?

Project 8 needs

- 2015:
  - Kr, Xe, T_2 running in existing magnet
  - R&D on scalable antenna, trap, DAQ
- 2016—2017
  - Scale up to ~1 liter
  - atomic T experiments
- 2018—
  - First shot at new ν mass sensitivity

- General sense: "we're not racing to beat KATRIN to the T_2 result"
- Most important outcome is a viable atomic-T experiment and dramatically-new sensitivity